



Topic
Science
& Mathematics

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Astronomy

Life in Our Universe

Course Guidebook

Professor Laird Close
The University of Arizona



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Professor Laird Close is Professor of Astronomy and Astrophysics at the University of Arizona. He majored in Honors Physics at The University of British Columbia's Vancouver campus, where he worked as a physicist to solve a variety of industrial problems, including impact/fretting wear in nuclear reactors and the biophysics of wood. Professor Close was awarded a prestigious study-abroad scholarship from the Natural Sciences and Engineering Research Council of Canada to study at the renowned Department of Astronomy at the University of Arizona, and in 1995, he received his Ph.D., specializing in the new field of adaptive optics.

Professor Close has invented and helped develop several new technology cameras for very sharp imaging of outer space using adaptive optics with most of the world's largest telescopes. As a new Ph.D. at the University of Hawai'i, he was on the team that discovered a moon around an asteroid and followed it for a full orbit. The moon was named Petit Prince ("Little Prince"). In 1998, Professor Close joined the European Southern Observatory as Deputy Director for Adaptive Optics and was the instrument scientist for the most successful adaptive optics camera (NACO) in the Southern Hemisphere. In 2000, he returned to the University of Arizona as a professor and developed several new adaptive optics cameras. Professor Close and his team have discovered all of the failed star, or brown dwarf, companions to nearby stars. He is a leader in brown dwarf and extrasolar planet high-contrast imaging astrophysics. Professor Close developed and is the prime scientist of the 6.5-m Magellan Adaptive Optics (MagAO) extrasolar planet imager, located in Chile.

In 2004, Professor Close was honored with a prestigious National Science Foundation (NSF) CAREER award, which is given to the top few percent

of young science professors in America. He also has won awards from the NSF's Major Research Instrumentation, Advanced Technologies and Instrumentation, and Astronomy and Astrophysics programs. Professor Close is a member of the NASA Astrobiology Institute, and he has gained support from numerous NASA Origins of Solar Systems grants.

At the University of Arizona, Professor Close has been highlighted as an outstanding professor and mentor. Many undergraduate and graduate students under his personal supervision have won outstanding researcher awards at both the departmental and university levels. ■

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Life in Our Universe

Scope:

Are human beings alone in the universe, or is the cosmos teeming with alien life? The answer is out there—and we might be the first generation of humans to find out. This course provides an in-depth examination of why and how life exists in our universe. Where else in our own solar system, or on which alien planets, could there be life? This course has been crafted to address some of the most fascinating questions about all types of life in our universe. Our journey of discovery is guided by the latest breakthroughs in astrobiological research, and you will explore these data in an informative and fun manner. Concepts, scaling laws, and broad understanding are stressed over simply stating a series of factoids and complex equations.

This course starts all the way back at the big bang and follows the formation of the Sun and the atomic elements critical for life (Lectures 1–3). You will then study the formation of the Earth and its Moon though giant impacts in Lectures 4–5. You will see how a series of coincidences led to an early Earth ready for life and why the Moon and Earth's hot core are important for life today. Then, in the next lectures (6–7), you will examine the evidence for when life actually started on Earth and survey, very broadly, what all life on Earth has in common. You will be introduced to extreme forms of life that will surprise you with how strange and hardy they are. Then, in Lecture 8, you will try to understand the enigma of how life could have started on Earth.

In Lectures 9–11, you will use your newfound knowledge to understand what life might be like elsewhere in the universe. You will first hop to the ancient highlands of Mars and see recent evidence that Mars might have had life in its past. You will take a critical look at the evidence of whether researchers have already found Martian fossils in Antarctica. In Lecture 12, you will visit Earth's twin planet Venus. You will understand why Venus is a hot, hellish world devoid of water and life. Then, you will push on to the giant planet Jupiter and visit its famous Galilean moons in Lecture 13.

The evidence of why scientists believe there is a large subsurface ocean of liquid water beneath Europa's icy surface will be revealed. Stepping slightly farther out will reveal a similar reservoir on neighbor moon Ganymede. You will preview the amazing new missions to these cold, icy moons to tease out whether there is liquid water and maybe even life. Next, in Lecture 14, you will move to the moons of Saturn and follow the *Huygens* probe as it descends through to the surface of the cloud moon Titan and then skims over the giant Ontario Lacus, where liquid methane carves an icy beach. You will finish by flying through a geyser of icy salt water from the moon Enceladus.

Lectures 15–17 take the search for life past our solar system to explore the plethora of alien solar systems being discovered by astronomers. You will learn how astronomers discover these worlds and what amazing surprises they have learned about alien planets. Based on the findings of the NASA *Kepler* spacecraft, you will estimate how common potentially habitable Earthlike worlds actually are. Then, you will visit some of the most interesting of these new alien solar systems in detail.

The question of how common intelligent life is in our universe will be discussed in Lectures 18–20. After reviewing some new ways that scientists are searching for extraterrestrial intelligent life today, you will then try to gauge how likely it is that the search will be successful. Possible solutions to the Fermi paradox will also be discussed. Then, in Lecture 21, you will take a critical look at how challenging interstellar travel is with today's technology and reasons why we will likely never travel to the stars in our lifetime. The daunting task of changing Mars into a more Earthlike world will also be examined as Lecture 22 reviews the science of terraforming. The penultimate lecture (23) looks at the Earth's future and examines the need to eventually find a new planet for humanity's home. Finally, in the last lecture (24), you will examine evidence that a real Earthlike planet will be likely discovered in the near future—setting the stage for humanity's most exciting adventure. ■

Is There Life Elsewhere in Our Universe?

Lecture 1

In this course, you will use the latest findings and capitalize on an exponential growth of information to try and answer one of the most fundamental questions facing mankind: Is there life in our universe? Throughout this course, you will learn about some of the most interesting scientific discoveries in astronomy, biology, theology, geology, chemistry, and physics to tackle this question in an interesting and unique way. Modern scientists are very skeptical that aliens have been on Earth, and they are intensely studying the question of life beyond Earth in a new field of science called astrobiology.

The Secrets of Life in Our Universe

- For the first time, humankind is on the brink of teasing out the secrets of life in our universe. In the 21st century, we are seeing for the first time a true nested group of exponential growth curves that mean separate technologies are all moving at exponential rates, allowing interdisciplinary scientists to make breakthroughs that were previously impossible.
- The first reason for this is that computers are getting faster. For the last 30 years, roughly every 18 months, we have seen the number of computing units on an integrated circuit doubling. Since the start of the 21st century, we have seen a tremendous increase in computer chip power. Scaling laws, such as Moore's law, are sweeping into many other fields.
- We have seen other similar exponential growth curves, where the main metric, or rubric, doubles over a short period of time. Digital cameras are another example. The individual unit—the single photo sensor—on a digital camera is called a pixel. The price of an individual pixel has been falling exponentially, which means that cameras have been getting larger and larger over time.

- We have also seen exponential growth in disc and memory storage space, allowing these massive new cameras, which are collecting all of this extra data, to be stored and processed. Through massive data-mining projects, we can go into large data sets that we simply hadn't had before because we could not store such massive amounts of data and mine through that data to tease out new secrets about nature.
- Even the most rudimentary life-form—single-celled microbes like bacteria, for example—can be found elsewhere in our universe, and the chances of life being common everywhere in the universe are dramatically increased.
- Discovery of intelligent life would alter our place in the cosmos forever. Right now, we can be the first humans to fully explore these possibilities with the new tools we have at hand. This might be humankind's greatest legacy, and it is coming soon.

The Inverse Square Law

- In 1995, the first planet was discovered around a Sunlike star. Now we know of thousands of planets and planet candidates, and what we are actually seeing here is, again, exponential growth: The number of planets that we are discovering around other stars is doubling over a very short period.
- Now that we are finding planets around other stars, we would like to know if they have the same temperature and atmosphere as the Earth. A good planet can be hard to find. What makes a good planet? Just like in real estate, the answer is location, location, location. We need to find a planet that is in the so-called Goldilocks zone—not too hot, but not too cold.
- How does a star actually warm a planet? How do we get into this Goldilocks zone, where the temperature is just right? A star is kind of like a big light bulb. It has a certain number of watts that it outputs—called its luminosity, which is a fixed number. In other

words, every second, a certain number of photons, particles of light, are streaming out from a star. The luminosity is constant, but the area over which it expands is always increasing.

- If the distance between a star and a planet is the distance D and the luminosity, a constant, is L , then the power absorbed by a planet varies as the luminosity of the star over D^2 (Power = L/D^2). This is sometimes called an inverse square law. As you get twice as far away, the number of photons—the amount of heat that a planet can absorb—falls off by a factor of four if there is a factor of two increase in distance.

The Field of Astrobiology

- In the new field of astrobiology, interdisciplinary scientists are trying to understand some of the biggest questions of modern science. Astrobiologists are hard at work trying to understand the vast variety of life on Earth. We know of a dizzying array of new types of life-forms that can thrive on Earth in conditions long thought to be too extreme for life, including a whole new branch of the tree of life, Archaea.
- The best place to look for this extreme life is on Earth. For example, strange exotic worms live in the very bottom of our oceans, where there are hot vents called hydrothermal vents or black smokers. Life also exists in the coldest, driest places on Earth, such as in the Antarctic in sandstone.
- Space probes have just found liquid lakes on a moon called Titan that revolves around the giant gas planet Saturn. We will follow liquid water as well in our solar system. We will learn about hot springs at the very bottom of our ocean, such as hydrothermal vents, to geysers on another one of Saturn's moons, where bursts of ice shoot out of the moon's surface.

Five Major Questions

What can Earth's current and past life tell us about life in our universe?

- In this course, we'll try to understand the big picture of how our own planet was formed and how this influences our ideas of how life first appeared on Earth.
- We will use DNA and RNA traces to look at our own genetic material and the genetic material of other extremophiles to understand how we evolved and how impacts, volcanoes, and the global rock carbon cycles played an important role in keeping life on Earth.
- We'll try to understand what common themes life has on this planet—in other words, what all things that are alive on Earth share. This will help us understand what types of life we might find and where in our own solar system.



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In our solar system, Earth is the third planet from the Sun and is ranked fifth in terms of size and mass.

Where else in our solar system can there be life?

- Once we have an idea of what the boundaries for survival of life appear to be, then we can ask where we see such habitable zones in our own solar system. In particular, Jupiter's moon Europa will be a focus of our study, and we will try to understand why scientists believe there is subsurface liquid water beneath the ice.

Is there life around other stars?

- Once we have hit the hotspots for life in our own solar system, we will start looking toward newly discovered solar systems. Exploring

extrasolar planets is one of the most dynamic fields in modern science. Geophysicists, astrophysicists, and planetary scientists are quickly trying to model what these new Earths—and a new class of planet called super-Earths, which are several times the mass of our own Earth—would be like and if they could support life.

- Super-Earths appear to be quite common, so it will be interesting to understand if a super-Earth planet could have life similar to ours, but we will look at it from a realistic point of view, and we will see that there are issues—such as the gravity being much higher or the atmosphere being much denser—that might preclude these planets from having life.

Is there other intelligent life in our universe?

- In this course, we will review evidence for intelligent life elsewhere in our universe. We will discuss the likelihood of such life as best we can. We do not know today that there is intelligent life elsewhere in our universe, so there are some educated guesses that have to be basically motivated, and we will try to motivate these guesstimates as best as we can throughout the course. We will estimate how likely it is that we will be able to communicate with such intelligent life using the most recent data available.

Is there a new home for mankind? If so, can we find it?

- The current climates of Venus and Mars will help inform us of possible future outcomes for the Earth's own climate. We'll also review the practical issues with new scientific fields, such as terraforming, which involves trying to make Mars a little bit more like Earth.
- We will understand what the practical limitations of space travel are. This is something that science fiction talks a lot about, but in reality, we are going to see how difficult it would be for mankind to build a spaceship that could travel from our own solar system to another solar system.

- Most importantly, we will also take a look at the science of climate change on Earth and try to understand how we can better take care of the Earth and what the ultimate fate of the Earth is.
- We are going to look at exciting breakthroughs that will allow the next generation of giant telescopes and space-based telescopes to directly look for signs of life on the so-called extrasolar Earths. We are going to understand how we could actually tease out signs of life from these planets.
- We are going to understand how scientists can actually take a picture of these new Earths and understand whether they have plant life and perhaps even animal life—and certainly whether they have liquid water on the surface.
- We will also try to understand just how common such Earthlike planets should be and what technologies are needed to allow us to directly image these planets and tease out whether they have biomarkers that tell us that it is a good place to go and motivate us to develop spaceships in the future to be able to travel between the stars.

Suggested Reading

Dick, *The Living Universe*.

Questions to Consider

1. Will the exponential growth in technology continue indefinitely?
2. Do you think we are alone, or is the universe full of life? If astrobiologists do find microbial life on Mars, how would that affect your answer?

Bang! A Universe Built for Life

Lecture 2

The start of the universe was the magnificent big bang. There was no sign of life then; the universe was far too hot and dense. In fact, the element carbon did not exist in the early universe. An amazingly lucky coincidence of nuclear physics allowed our universe to create the key atomic elements for life, setting the stage for life to arise later in history. In this lecture, you will learn about how the originally dead universe was transformed into a universe full of life.

The Birth of Our Universe

- All matter is composed of tiny atoms, and atoms form substances called elements. Despite the vast array of molecules around us, there are actually only 118 individual elements, and only the smallest of these are actually useful for life.
- Many of the elements that have the highest atomic numbers are quite unstable and radioactive, so they have no real use for life. In fact, they're harmful to life. Only carbon, nitrogen, oxygen, sulfur, hydrogen, and phosphorous are crucially needed for life. However, there has been a little bit of debate on whether phosphorous is necessary.
- Individual elements combine to form very, very long polymers—such as DNA—that lead the chemical pathways and reactions that actually make life come alive. With just a few building blocks, we can make an infinite number of combinations of long polymers and monomers. The key to this is the ability to use carbon, which is the most flexible element for combining and making very, very long polymer molecules.
- The universe as we know it started about 13.6 billion years ago. Astronomers have pinned this number down quite well with some spacecraft missions. The universe started in the big bang, which

was a kind of symmetric expansion of time and space—everything expanded in all directions at once.

- There was a very brief period of extremely rapid expansion right after the big bang. The universe started cooling down rather quickly. As the universe expanded, the gas that the universe was made of basically cooled down pretty quickly. It wasn't a gas that we are familiar with; it was more like a sea of the very fundamental particles and quarks.
- It was hotter than we can possibly imagine and completely unsuitable for life. Atoms simply couldn't form under these extremely high temperatures. However, in the first 3 minutes, things started cooling down enough that unstable free neutrons could start to combine with protons to build the nucleuses of helium and mainly hydrogen—the atomic nuclei from which the rest of the universe formed.
- The fact that our universe is very close to 25 percent helium and 75 percent hydrogen can be explained by the fact that the universe must have started out with a tremendous explosion. We must have gone from a tremendously compressed, hot state into a much, much cooler state that we have today.
- If you have 75 percent hydrogen and 25 percent helium, that works out to be about one neutron for every seven protons. However, there is a bottleneck to building bigger and bigger elements with higher atomic numbers; there's no stable element that has an atomic number of five or eight. This was a great limiting problem.
- We need to have carbon in this universe if we're going to have life, so we have to figure out a way to make carbon. Luckily, what came to our rescue in our universe was gravity. We have these large clouds of hydrogen and helium in the early universe, and gravity started to act on these clouds by dominating the thermal motions and bringing them together and collapsing them.

- Soon, the first stars were created. These stars were made of hydrogen and helium. As the clouds of gas and dust compressed, shrinking by thousands of times in size, they experienced a little bit of angular momentum, or spin, to build stars. This process would also spin out a disc of material around the star. These flattened-out stars played a large role in the formation of planets.

After the Big Bang

- As soon as the temperatures started to approach 100 million Kelvin, a special process called the triple alpha process allowed for an excited form of beryllium to collide with another helium to produce carbon 12. This is a very rare reaction and takes thousands of years to produce a large amount of carbon, so it could not work during the big bang because there was only a brief period—less than 3 minutes—when there was a hot enough phase to build up these elements through fusion.
- Through the triple alpha process, we break the bottleneck of getting over just producing lithium and beryllium to producing the heavier elements in the periodic table. In other words, the triple alpha process breaks the bottleneck and allows us to live in a universe with carbon.
- Stars are absolutely critical to having a universe with life because they are able to form carbon at their cores. On some level, they are the ovens of life because they help fuse together higher and higher elements throughout the periodic table that are needed for life. Through the simple process of adding an alpha particle to elements, we can build a universe that has all of the necessary elements for life.
- After the big bang, all we have is simply hydrogen, helium, and some trace amounts of lithium and beryllium, which are not very well built inside the cores of stars. However, thanks to stars, we can fill out the very rest of the periodic table, which allows us to have a universe that can thrive with life. Over time, the universe became richer and richer in these so-called heavier elements.

- Our Milky Way Galaxy is still mainly hydrogen and helium, but it is now more like 74 percent hydrogen and 24 percent helium. All of the heavy elements contribute about 2 percent by mass to our entire universe. These are absolutely critical for life, but they seem to be just fringe products. However, 2 percent of the universe is actually an awful lot of mass—certainly enough to build all of the planets and all of the life you can possibly imagine.
- Carbon is only about .5 percent of the atoms in the universe by mass, but even though carbon atoms are still about 200,000 times less common than hydrogen atoms, they are still quite abundant.
- Stars will burn, which is basically a process that involves fusing lighter elements to heavier elements, and the end product has a little less mass than the two products you started with. The difference in that mass, the slight difference in weight of the elements, turns out to be released as almost pure energy through $E = mc^2$. That's a tremendous amount of energy, and that's how stars shine because they're constantly fusing light elements into heavier elements.
- The fusion process enriches the cores of these stars, and at the same time, the stars are keeping themselves from collapsing all the way down because they're creating a tremendous amount of heat, energy, and pressure.
- Pressure can balance through a process called hydrostatic equilibrium. The force from gravity, which is trying to crush the



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The Milky Way Galaxy, the galaxy in which the Earth lies, contains several billion stars—one of which is the Sun.

star, can be balanced with the power that's going on in the core of the star to keep the star stable.

The Death of Stars

- Stars don't last forever. Eventually, they start to run out of the lightest elements and start to contain heavier and heavier elements, which they have to burn and fuse together, which makes even heavier elements. This process cannot continue forever.
- Very massive stars, on the order of 8 times the mass of our own Sun, start fusing higher and higher elements to make iron. When they start fusing iron in their core, they're starting to lose energy, the result of which is a spectacular explosion known as a supernova.
- The most typical death of Sunlike stars is when it fuses the smaller elements into heavier and heavier elements, but it will reach a certain limit. It just doesn't have the mass to go all the way up to iron, for example. When it's fusing together helium, it's very sensitive to the temperature in the core. As it starts to increase the temperature of the core, like any gas, it expands. As it expands, it cools, and then it produces less energy and contracts down again. There's a cycle of getting very hot in the core and expanding and then cooling and contracting—which will go on for a very long time.
- In this process, the star will start losing its outer layers of its atmosphere into interstellar space. As that gas cools down, if it's enriched in silicates like silicon carbide, for example, it can condense and make tiny grains of dust or sand, which will be blown off by stellar winds into space and then get mixed up with the remaining gas and other dust from other outflows from other stars at their end of their lives.
- As a result of this process, our galaxy is enriched in these heavier elements—in these molecular clouds, which contain gas and dust. Eventually, there will be a violent enough pulsation that will blow the whole envelope off of the surface of the star and be left with a very small, hot core of the star—which is perhaps just carbon and

oxygen—called a white dwarf. Once the rest of the envelope floats away from the star, we’re left with a planetary nebula (which has nothing to do with planets).

Suggested Reading

Bennett, Donahue, Schneider, and Voit, *The Cosmic Perspective*.

Impey, *The Living Cosmos*.

Questions to Consider

1. Why was the early universe completely devoid of carbon? Where was the carbon in your body later produced?
2. Why does our universe have just the right conditions (and physics) for life? Physicists are highly disturbed that so many physical parameters are fine-tuned for life. Some believe that there are many universes in what they call the multiverse, and we just occupy one section of the universe where the conditions happen (randomly) to be just right. What do you think?

A Star Is Born—Forming the Solar System

Lecture 3

In this lecture, you are going to learn how the planets in our solar system were built—as best as scientists understand the planet-formation process. It is important to note that this is an incomplete understanding. You will also learn how the Earth and the other planets in our solar system formed and how this process left the solar system teeming with asteroids and comets, which play an important role in both helping and hurting life on Earth.

Stars and Supernovas

- In a typical galaxy, you might have about one supernova every century. For a very brief period of time, a single star that is going supernova can outshine a hundred billion stars in our galaxy. These are incredible explosions, and they are incredibly important for life because they give us the heavier elements that are critical for making, nickel, iron, and rocky planets like the Earth.
- In the end stages of the supernova explosion, there is a remnant dusty shell of gas and dust that has been pushed off of the star after it has exploded, and it is that remnant that is enriched in these heavy elements, which will cool down and form tiny particles called dust particles. These dust grains contain heavy elements like silicon and, in fact, might be bonded with carbon to make silicon carbide. These tiny silicon carbide grains will go off and start to seed planets around other solar systems as they are slowly caught up in swirling clouds of dust and gas.
- Scientists can find these individual grains of this space dust even in our own solar system. Using radioactive elements in those grains, scientists can date them to be older than 4.55 billion years. These are grains that managed to avoid being melted in the process of the formation of our solar system and have remained grains the entire time the Earth has existed.

- These grains were produced by a supernova that occurred earlier than the Sun was born, so they are older than the Sun. We can examine them to understand something about what the conditions were like in the initial dust cloud from which our Sun was formed. These grains are perhaps about 5 billion years old or even older—basically floating in space before they became trapped in our nebula, but they somehow avoided being rained down on the Earth and melted.
- The dust and gas released from the end phases of a star's life—either a supernova from massive stars or a planetary nebula for lower-mass stars—are swept up into large clouds and, over time, are sometimes triggered by a supernova like a punch to the side of the cloud, which makes that cloud start to compress and form new stars. These molecular clouds will, nevertheless, collapse to form new stars.
- About 4.55 billion years ago, this occurred for the Sun, which formed from its own nebula of gas and dust called the solar nebula. This solar nebula enjoyed over 8 billion years of these heavy elements being produced. These were the heavy elements that we need for life and also that we need to build rocky terrestrial planets.
- Small dust grains start as small as a tenth of a micron, which is an extremely small particle, and then they can grow over time by bumping into other grains and sticking together, growing to several millimeters in sizes. We have evidence that they can grow as large as centimeters, at which point they become able to be observed.
- From these very early days—at 100,000 years of age, for example—these young stars are incredibly gas and dust rich. It takes about 10 to 12 million years for almost every star to run out of its gas component and be left with only its dust component when it is in the nebula phase.

The Formation of Planets

- Giant planets that we have in our solar system—such as Jupiter, Saturn, Neptune, and Uranus—had to have been made fairly quickly because if they had waited for more than 12 million years to be made, then they would have run out of gas, which they need to form. After all, these planets are mainly made out of hydrogen and helium.
- What we are starting to understand about how planets are actually formed is that it is a fairly quick process. It has to happen in about 10 million years to build these gas giants, and it probably has to happen in the icy outer regions of the solar system, where there is lots of ice, gas, and dust. That is where with these big, icy, heavy grains can be packed together quickly, building up enough mass and increasing into meter-sized objects.
- It is not exactly understood how these grains grow from meter sizes up to much larger sizes. Once they reach a kilometer in size, gravity starts to take over, and they start to suck in all of the objects around them, growing larger and larger very, very quickly. Soon, they could grow up to 10 to 30 Earth masses, at which point there is enough gravity in the young planet so that helium and hydrogen can fall down onto the planet.
- Although it is clear that nature was able to develop these 1-kilometer-sized objects—called planetesimals—these are planets to be, and nature figured out how to create them very effectively. After all, people estimate that there might have been as many as 10 billion young comets in the early solar system. Today, we are struggling to



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Jupiter is the most massive planet in the solar system and is the fifth in distance from the Sun.

understand this exact process. Even though we can understand how small dust grains can be put together to build things that are a meter in size, we struggle in our models to get to much larger than a meter in size.

- Nobody fully understands how our solar system built so many 1-kilometer-sized bodies in the first 10 million years, but we know that it did. We can still see the remnants of these objects as comets and asteroids today. We see discs of gas and dust around other stars, and around the older stars, we see only dust discs as expected because the dust goes away after 10 million years.
- These dust discs, though, would also disperse fairly quickly, but we see these discs around stars that are sometimes hundreds of millions of years old. How can this be? What we believe is that we are actually seeing grinding between asteroids in these older systems that are producing new dust, and this grinding process from this planetesimal population is leading to a phenomenon called debris discs, which we see around other stars.
- This is evidence that the process of building these kilometer-sized objects is common, which also leads us to believe that perhaps how we understand planets were made in our solar system might be somewhat common in other solar systems, too. We know from the inverse square law that the inner solar system was hot—too hot for there to be a substantial buildup of icy cores and to have enough gravity to accrete the hydrogen and helium that we need to make giant planets.
- In the area where it was hot, terrestrial planets were formed. Terrestrial planets cannot be icy and cannot be gas giants like the outer planets because they simply never had enough mass to make the seeds at a high enough gravity rate that they could pull down the hydrogen and helium from the early solar system.
- The formation of the inner rocky planets, like the Earth, allowed for a stable platform for life to form much later on. The most massive

planets, the gas giant planets, were formed past the snow line in the outer part of our solar system—where it was cool and they could build up big cores. This is how Jupiter, Saturn, Uranus, and Neptune were formed.

- Inside the snow line, where it was much hotter, given by the inverse square law, it was dry, volatile, poor, and lacked many ice masses. This, therefore, formed rocky terrestrial planets like Mercury, Venus, Earth, and Mars.

Asteroids and Comets

- The surface of the young Earth was very, very hot. Perhaps it was almost completely covered in liquid magma rock. Some think that it might have been completely molten—more of a magma ocean. Many of the organics, volatiles, carbon-rich elements, and waters were all lost in the process of being impacted by asteroids and comets because these elements were turned into vapors, and the atmospheres were completely blown away by these large impacts.
- The outer planets, like Jupiter, through several different processes that astrophysicists have now modeled, probably allowed a virtual rain early on of material down on the Earth. Some of this material might have actually been the source of some of the carbon that we have today for life.
- By about 12 million years, the solar system had probably lost its gas; most of it had accreted on the Sun or was blown away. The giant planets have stopped growing at this point, and the solar nebulas are cleaning up the remnants of this planet-formation process. Mainly asteroids, comets, and dust are left.
- Asteroids are the remnants of this rather messy process of terrestrial building, where you are smashing things together and making bigger things through gravity and sometimes smashing things together and pulling everything apart.

- Very large asteroids on well-behaved orbits do not go anywhere near the Earth. Smaller asteroids, on the other hand, do present something of a danger to life and certainly in the past have played a big role in major extinction events. The asteroids that we can visit in our own solar system probably exist around other stars.

Suggested Reading

Bennett, Donahue, Schneider, and Voit, *The Cosmic Perspective*.

Questions to Consider

1. Why can't astrophysicists build objects much bigger than a boulder in their models to build mile-wide planetesimals?
2. Why do astronomers think large gas giant planets form in the outer part of a solar system?

The Early Earth and Its Moon

Lecture 4

The Earth formed with a hot core. Then, 30 million years later, a large impact created the Moon, which orbits the Earth and stabilizes our tilt and gives us tides—both of which are important for life. In this lecture, you will learn about a series of apparent mishaps and cataclysmic events that together set the stage for the dead early Earth to follow its destiny to a world full of life. By the end of this lecture, you will understand just how such a wonderful world was formed for life.

The Formation of the Earth

- We have now followed the ancient history of our solar system—which is about 4.55 billion years old—to where the young Sun has formed and there are swarms of planetesimals throughout the inner solar system. There are still a few Mars-sized planets that have yet to fall into a stable orbit.
- Earth is not your average planet. In fact, there are several properties that make the earlier Earth far more likely than any other planet in our solar system to have an active surface biosphere today. These are important lessons in the cosmic book of life for us to start to fully understand the needs and characteristics of at least life on one planet: Earth.
- The Earth is the solar system's largest terrestrial planet, despite there being billions of comets and asteroids formed in the early solar system. Only a few large planetesimals survived into the planets we have today: Mercury, Venus, Earth, and Mars.
- The Earth is a lucky planetesimal. It managed to grow in mass and accreted through gravity the rest of the mass that it needed to be the master of this orbital regime. It dominated the distance that we call 1 astronomical unit from the Sun, and all other lesser bodies were

accreted onto it. It never was destroyed by any of the impacts of asteroids or comets.

- During this formation process, massive amounts of heat were deposited on the surface of the Earth as it converted the kinetic energy of the infalling asteroids and comets to heat energy. To have a rocky planet at just the right distance from the Sun was critical for life.
- For life to thrive on a planet, it needs a hot core. The Earth has a hot core for four reasons:
 - The radioactive decay of uranium, thorium, and potassium is one reason that the Earth has a hot core. Each radioactive decay—the loss of some neutrons and protons—releases very little energy. However, all of the countless events acting together release a large sustained amount of energy over time. In the core of the Earth, this energy is trapped, so the Earth's core is heated up.
 - As the solid inner core grows, latent heat is released as the molten outer core freezes to solid rock.
 - Some of the kinetic energy (which equals $(1/2)mv^2$, where m stands for mass and v stands for velocity) of the impacting planetesimals would have been converted to heat. This residual formation heat helped melt the core initially.
 - Another early heat source was the heat produced as the heavy elements—like iron and nickel—were sinking into the core as the Earth differentiated. This process also generated heat from friction.

The Formation of the Moon

- About 50 million years after the Earth had formed, one of the most amazing events in the history of Earth occurred: the formation of the Moon. While natural satellites are common in the solar system, the Earth-Moon system is highly irregular.

- Earth's Moon is the largest terrestrial moon by far. The Moon's diameter is 27 percent of the Earth's diameter and is located 30 times that distance away from the Earth. The Earth is 82 times more massive than the Moon; the Moon is 1.2 percent of the Earth's mass.
- The Moon has nearly the same mantel material (the same oxygen isotopes, oxygen 16 or oxygen 18) as the Earth, but the Moon's iron core is much smaller. Its core is just 1 to 4 percent of the Moon's mass while the Earth's core is about 30 percent of the Earth's mass.
- The best theory that can explain the origin of the Moon's properties is called the giant impactor theory, or big splat, and is a relatively new idea. The most sophisticated three-dimensional models suggest that about 50 million years after the Earth formed, an impactor of about the mass of Mars slammed into the Earth in a glancing blow. The impact was enormous: The energy involved was 100 million times that which wiped out the dinosaurs.
- The big splat is now generally accepted as the best solution. It is only in this big splat that we can have a Moon that has very little iron in its core but still have the same mantel material as the Earth does because it formed from the same material. In fact, the basalts on the Moon are in many ways very similar to that on the Earth.
- The Moon plays two important roles for keeping Earth a stable place for life. As tides work as $1/r^3$, it is clear that the Moon dominates terrestrial tides—with the Sun the next most important factor.



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Earth's Moon is the brightest object in the sky after the Sun.

The Moon allowed for the existence of tide pools, which undergo dehydration reactions that could have served as a crucible for life. The second role that the Moon plays is that it stabilizes the Earth's spin axis. Keeping the Earth's poles stable keeps the climate stable for life.

Atmosphere and Magnetic Fields

- After the Moon-formation event, the Earth's clock was set back to zero, and a whole new crust began to form. The Earth's volatiles—things that melt or boil at low temperatures, such as water—can be trapped in the rocks that formed the Earth. These volatiles come out of volcanoes as gases, and these gasses create the first atmosphere for Earth after a massive collision.
- Then, as temperatures cool, this leads to condensation—in this case, water in the form of rain. This rain starts making the first lakes. However, conditions are likely too unstable on early Earth to have any very long-standing, stable crust (let alone oceans). It is not until about 600 million years have passed that Earth starts becoming a stable place, setting the stage for life.
- A nice side effect of having a hot core is that the outer part of the Earth's core is liquid magma metal. This is rich in flowing electrons, so a magnetic field is created around the Earth by magnetic induction of the spinning core.
- The process of magnetic induction involves the following: When an electrical conductor is moved through an initially existing magnetic field, electric currents are induced. These currents give rise to a new magnetic field that can replace the initial field.
- The Earth's magnetic field is all that stops the solar wind's electrons and protons from stripping away our atmosphere with its wind of charged particles.

- The Earth's magnetosphere deflects most of this wind well above the atmosphere, so the Earth can hold onto its atmosphere as long as it has a hot core.
- It is very likely that to have a stable world for life, it is important to have a planet with a hot core. In addition to the creation of protective magnetic fields, the carbon-rock cycle stabilizes the temperature of the planet. It is also likely that having a large moon is an advantage because this stabilizes the spin axis of the Earth and creates tide pools for dehydration reactions and rich biodiversity.

Suggested Reading

Bennett, Donahue, Schneider, and Voit, *The Cosmic Perspective*.

Bennett and Shostak, *Life in the Universe*.

Questions to Consider

1. When you were young, did you have any thoughts of how the Moon formed?
2. Given that the formation of a large moon like ours is a very rare event, do you think that in order for a planet to have life, it must also possess a large moon?

Impacts—Bringers of Death ... or Life?

Lecture 5

Earth had all the makings of a great planet for life, including all of the necessary elements, a hot core with magnetic fields to shield the young atmosphere, enough mass to hold onto that atmosphere, and a large Moon to stabilize its tilt and seasons. Earth appeared ready for life after the Moon formation ended (about 50 million years after the Earth was formed), but the next 600 million years were filled with very large impacts as the solar system cleared out its excess asteroids and comets. In this lecture, you will learn what effects even a single large impact has on life.

Impacts and Bombardments

- Asteroids and comets, remnants of the formation of the solar system, wreaked havoc during the first 600 million years of the Earth's history. During this time, the Earth was bombarded over and over again. Even one single large impact can shape the evolution of life on a planet.
- During the late heavy bombardment period, which took place approximately 4.1 to 3.8 billion years ago, the impact rate was particularly bad. We know about the late heavy bombardment because the craters on the Moon tell us that it was only after the Earth was 650 million years old (3.8 billion years ago) that the level of giant impacts die down.
- The late heavy bombardment may have been due to Jupiter and Saturn getting into a short-lived two-to-one resonance with higher ellipticity.
- With impacts, energy is always conserved. The kinetic energy of a body is half its mass times the square of its velocity: Kinetic energy = $(1/2)mv^2$.

- When an object hits the Earth, its velocity is zero, and all of its kinetic energy must go somewhere. Velocity equals time multiplied by gravity, so time varies as the square root of the distance, and speed varies as the square root of distance. Therefore, to double the impact speed, multiply the drop height by 4.
- You can see the difference of doubling the speed of an impact if you were to drop a ball from 10 cm and 40 cm into a glass of water. You should see 4 times the difference in energy.
- Basically, impact energy goes into heat and shock waves, which can be very destructive because the velocities are typically 20 miles per second. Imagine just how fast 20 miles per second is; such an object can zip from one side of a city to the other in a blink of an eye. How much energy comes from an asteroid that is 6 miles, or 10 kilometers, in size?
- The most famous example of a massive impact having an effect on mass extinction is the so-called K-T impact event, which is the impact that killed off the dinosaurs. In the rock history of the Earth, there is a layer called the K-T layer between the Cretaceous and the Tertiary, and at this layer, there is this thin layer of clay that contains a material called iridium.
- The element iridium is not very common on Earth. It is much more common in asteroids and meteorites, and it is interesting that there is this global layer of clay. This thin layer of clay enriched in iridium dates back to about 65.5 million years ago. Below this layer of clay, you can find dinosaur fossils, but above this layer of clay, there are no more dinosaur fossils.
- Scientists believe that what led to the end of the reign of the dinosaurs on Earth is that in the asteroid belt, a large body actually broke apart, and parts of it hurtled toward the Earth. Probably, an impactor on the size of about 6 miles (10 kilometers) hurtled toward the Earth.

- A 6-mile asteroid impact would have released 10^{24} watts, or 100 million megatons of TNT—which is more than 7 billion times the energy of the Hiroshima bomb and equivalent to the total energy the Earth receives from the Sun in about 2 weeks.
- Another way of thinking about this impact is if you gave every person on Earth a simple atomic bomb and 10 bombs for every square kilometer of the Earth's surface and you set them all off at once, only then would you have the equivalent amount of energy.

How Impacts Affect Life

- A single massive impact can change the course of life on a planet; therefore, it stands to reason that the most successful early life on Earth would have some protection against such events. For example, single-celled microbes that could live deep in the subsurface ground water (or hot springs at the bottom of an ocean trench)—referred to as extremophiles—would do better than those that needed to live near the surface of shallow seas.



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The Barringer Meteorite Crater—located just west of Winslow, Arizona—is about 4000 feet in diameter and about 600 feet deep.

- There is a trace of this past etched into our very DNA. After the formation of the Moon, we had lost a great deal of our volatiles—liquids and gases—to space. Hence, nearly all of the organics that early life would have needed would have been blasted from the face of the Earth.
- Asteroids and comets would have played a key role in resupplying Earth with its needed budget of volatiles, such as water and amino acids. Many asteroids are very carbon rich, and comets have lots of water. Without this, the surface of the Earth could be simply barren rock and refractory materials. Then, life never could have started.

The Future

- Today, some astronomers spend every night scanning the heavens, looking for near-Earth asteroids (NEAs). Greater than 90 percent of these that are greater than 1 kilometer (0.6 miles) are being tracked as per a congressional mandate, and so far, none look like they will hit the Earth.
- The K-T impactor, which was the crater that helped us put together the whole story about the demise of the dinosaurs, was about 15 kilometers. While a K-T event is very unlikely in the next few million years, there is always the chance of a moderate impact. However, we have no way to stop an asteroid even if we are able to detect it in time.
- The issues with stopping asteroids is that they have a huge amount of momentum; they are the size of cities traveling at 20 miles per second. Hence, they are pretty hard to stop. At best, we can—over a long time—slightly divert the path of the object. In Hollywood, they often blow up the asteroid, but this would at best make matters worse, including starting a meteor storm.
- One possibility is a gravity tractor. This relatively new idea uses the force of gravity of a hovering spacecraft (that is flown out to the asteroid), which slowly pulls the asteroid in the direction of the spacecraft and away from a collision course with Earth.

- An idea that Hollywood likes is using nuclear bombs. The drawback is that in the vacuum of space, nuclear bombs are pretty weak. It would work better to plant one inside the asteroid—but even then, it could make things worse if there are suddenly thousands of small rocks all heading for Earth instead of one big one.
- Asteroids and comets probably brought much of the organics that life needed after the Earth's surface was destroyed from the big splat Moon-creation event. They have also played a destructive role by forcing mass extinctions. Certainly, no life survived the entire late heavy bombardment, which occurred about 4.1 to 3.8 billion years ago.
- These extinctions really changed life on Earth. The K-T event that occurred 65.5 million years ago wiped out the dinosaurs, which had ruled the Earth for many, many millions of years. If this event had not occurred, it would be very unlikely that we would be here today—at least in our present forms. In fact, it was quite lucky for the mammals, which include human beings, that the dinosaurs were wiped out by this event.

Suggested Reading

Bennett, Donahue, Schneider, and Voit, *The Cosmic Perspective*.

Questions to Consider

1. Assume that the late heavy bombardment ended 65 million years earlier—so Earth's timeline becomes 65 million years more advanced—then would modern humans (instead of the dinosaurs) be wiped out by the impact that occurred 65 million years ago?
2. Will a future impact wipe out humans from the face of the Earth in the next 1 million years? Is that the most pressing worry for the future of mankind, or are there other, more likely, cataclysms to occur sooner than an impact?

Evidence of the First Life on Earth

Lecture 6

In this lecture, you will learn that there is a powerful system of checks and balances that keep the Earth's climate in a moderate range. This global system is the Earth's thermostat for life, and without it, no complex life would have ever likely arisen on Earth. It is important, in the context of life, to understand the consequences of an active planet. The Earth has a very hot core that drives a dynamic process that provides the Earth with magnetic fields, but this hot core, by force of convection, also changes the landscape of the Earth's surface.

The Earth's Surface

- Earth's hot core drives dynamic processes like plate tectonics and magnetic fields, which play important roles in keeping the Earth continuously stable for life for billions of years. Life thrived in oceans about 3.85 to 3.5 billion years ago, approximately 100 million years after the oceans became stable.
- The Earth has had life for billions of years. That is a lot of years to have had at least some liquid water on—or near—the surface of the Earth. How does the Earth manage this feat of staying in such a moderate range of temperatures when the atmosphere was undergoing tremendous changes?
- Convection drives the process of plate tectonics, in which the convective cells in the upper mantle of the Earth create spreading zones (trenches at the bottom of the ocean) and subducting zones (such as the Rocky Mountains). These forces shape the Earth and have had a strong effect on life on Earth.
- The spreading centers have the heaviest rock and, therefore, are located typically at the bottom of the ocean trenches. These trenches can have hot springs due to the close proximity of the hot magma.

These can provide unique habitats for life. Hot springs can be stable even in a large impact.

- Earth would not be habitable without its atmosphere, which works as a blanket to trap in thermal photons in the 10-micron part of the spectrum. This is the greenhouse principle in action.

The Carbon-Rock Cycle

- The greenhouse effect works in conjunction with plate tectonics to keep the Earth habitable as part of the carbon-rock cycle. This cycle acts as the Earth's thermostat, and it has played a key role in keeping the Earth's temperature in balance over time.
- With the carbon-rock cycle, if it gets cooler, then the colder oceans stop locking up—or sinking—as much carbon (CO_2) from the atmosphere. The sink works as follows: In oceans, dissolved carbonate and calcium (from weathered rock) goes to calcium



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Hot springs are springs that contain water at temperatures that are much higher than the surrounding air temperature.

carbonate mainly as the shells of microscopic organisms, which die and then the calcium carbonate turns to limestone.

- As long as the pH of oceans stays constant and does not get too acidic, the limestone will continue to act as a sink. Limestone is the biggest reservoir of carbon in the carbon cycle. If it is cold, then the ocean life slows down and, therefore, there is less sink.
- How does it warm up? The carbon sinks are weaker, but the Earth's core is still hot, so plate tectonics keeps subduction zones running. The volcanoes from these subduction zones keep pouring out CO₂ gas from the limestone that melted in the subduction zones, so the atmospheric carbon source is unaffected by the cold. This allows the CO₂ to build up in the atmosphere. Then, the greenhouse increases, and the Earth warms up to about 285 Kelvin (or about 50°F) again, which takes about 400,000 years.
- The opposite works, too: If it gets hotter, then the plants and hot oceans increase locking up, or sinking, more carbon (CO₂) from the atmosphere—as long as pH is constant, which it is, given natural warming over thousands of years. The volcanoes from these subduction zones keep pouring out CO₂ gas at a constant rate. However, it can't keep up with the increased sinks. CO₂ starts to decrease in the atmosphere. Then, greenhouse weakens, and the Earth cools down again to about 285 Kelvin (again, it takes about 400,000 years).
- All the Earth really needs to maintain a steady 300-degree (Kelvin) temperature is a hot core and plate tectonics (both of which it has had for about 4.55 billion years and will have for another 4 billion years), life and/or chemical weathering (surface liquid water) to lock up the CO₂, and sunlight (which it will have for at least another 4 billion years). Things have been pretty steady ever since approximately 3.8 billion years ago, when the Earth first developed permanent oceans.

Early Life on Earth

- The history of life on Earth involves going from a hellish world for the first 650 million years (4.5 to 3.9 billion years ago) to one teeming with complex multicellular life. We don't know all of the steps that happened, but from the fossil and chemical records, we know some things about the Earth's history.
- Evidence for the Earth's first life includes the existence of stromatolites, or colonies of bacteria, around 3.3 to 3.5 billion years ago. We can also find individual fossilized cells that existed 3.5 billion years ago in rocks with great care.
- In addition, carbon isotopes that existed 3.85 billion years ago have been found in rocks. Life prefers the lighter (nonradioactive) carbon 12 over carbon 13, and in fact, if you look at a fossilized rock that is something that was alive at some point, you will always see that there is more carbon 12 to carbon 13 than in a rock that was never part of a living creature.
- It is interesting that higher carbon 12 to carbon 13 rocks are found in Greenland that date to 3.85 billion years ago. These are the oldest rocks we have—from the tail end of the late heavy bombardment.
- It is truly amazing that life could have sprung up about zero to 100 million years after the end of the heavy bombardment. This implies that life was able to start quite quickly—at least in the form of the simple single-celled life stage.
- If we accept all of this evidence, then we must conclude that life gained a foothold on Earth in a relatively short amount of time (in approximately 10 to 300 million years). Life originated quickly once the Earth became habitable.
- Also, it didn't take long for life to become widespread and relatively sophisticated. The bacteria present 3.5 billion years ago were quite sophisticated. They had chemistry based on DNA molecules. Some were even photosynthetic and produced an O₂ atmosphere.

- This means that photosynthesis must have become widespread enough to alter the environment of the entire planet, paving the way for multicellular organisms (like human beings) using respiration.
- Up until this point in time, there had only been prokaryotes, which are single-celled creatures with no nuclei, but around 1.5 billion years ago, the first fossil evidence of eukaryotes, cells with nuclei, appeared.
- Once eukaryotic life appeared—which took about 2 billion years after the first appearance of life on Earth—it only took a few hundred million years for multicellular plants and animals to develop, with the Cambrian explosion producing an astonishing variety of types of animals about 540 million years ago.
- It is interesting to note that for multicellular life to thrive, much more efficient levels of energy production was needed—like respiration—and the newly oxygen-rich atmosphere allowed this transition to happen. Without that oxygen-rich atmosphere, perhaps complex multicellular life never would have arisen.

Suggested Reading

Bennett and Shostak, *Life in the Universe*.

Plaxco and Gross, *Astrobiology*.

Questions to Consider

1. Just as the early cyanobacteria “polluted” the Earth with oxygen (to help give rise to humans), will mankind’s “polluted” atmosphere give rise to different life forms in the far future?
2. Are you surprised that only about 10 to 100 million years after the end of the late heavy bombardment life arose on Earth? Does that seem fast or slow to you?

Common Themes for All Life on Earth

Lecture 7

All living things on Earth share many similar traits, such as ATP and DNA, providing strong evidence of a universal common ancestor. There is a web of interconnected systems that keeps life alive in our world, but life itself must be robust because it can still be a harsh world. In this lecture, you will more closely examine some of the overall themes of all life present on Earth so that you can understand what is essential to life on a planet—specifically, on our planet.

Photosynthesis, Respiration, and Fermentation

- Life must have some sort of chemical pathways to survive, grow, and get energy. All life on Earth uses a similar system of chemical reactions; they are all carbon-based chemistry, use liquid water as a solvent, and use adenosine triphosphate (ATP) as a way of storing and releasing energy.
- The input of photosynthesis is carbon dioxide (CO_2), water (H_2O), and sunlight. The output is carbohydrate (CH_2O) and oxygen (O_2) molecules. Plants use the catalyst chlorophyll to take CO_2 from the air, H_2O from the ground, and sunlight (to build more complex bonds) and produce complex hydrocarbons, such as plant cell walls.
 - $\text{CO}_2 = \text{C} + \text{O}_2$
 - $\text{H}_2\text{O} = 2\text{H}^+ + (1/2)\text{O}_2 + 2\text{e}^-$
- The H^+ produced increases the production of ATP, which is then used to drive chemical reactions inside the plant cell (such as build more cellular wall tissue).

- Respiration is the reverse of photosynthesis. An example is aerobic respiration.
 - $\text{CH}_2\text{O} + \text{O}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O} + \text{energy}$
- Oxidation of the carbon molecule produces energy, which builds up ATP and can be used to build up cells or stored for later use. Therefore, animals eat plants to gain energy, or bacteria eat free-standing molecules to acquire energy.
- With fermentation, there is no free O_2 or sunlight. In the following reaction, the input is glucose, and the output is ethanol and energy.
 - $\text{C}_6\text{H}_{12}\text{O}_6$ (glucose) $\rightarrow 2\text{C}_2\text{H}_6\text{O} + 2\text{CO}_2 + \text{energy}$
- The bacteria in the lower levels of stromatolites use fermentation to survive without O_2 or sunlight.

Harsh Environments

- We have just discovered that life is quite a bit more widespread than photosynthesis, respiration, and fermentation would lead us to believe. New classes of microbes called extremophiles can thrive in very hot, cold, acidic, or isolated environments. These are single-celled marvels of adaptation that can thrive in environments that would be deadly to human beings.
- If there is no sunlight and no organic molecules, then hydrogen reducing must take place.
 - $\text{Fe} + \text{H}_2\text{O} \rightarrow \text{H}_2$ (hydrogen gas)
 - $6\text{H}_2 + 2\text{O}_2 + \text{CO}_2 \rightarrow \text{CH}_2\text{O} + 5\text{H}_2\text{O} + \text{energy}$
- Hydrogen gas comes from the oxidation of iron by the groundwater located deep within the Columbia River Basalts. This hydrogen gas is then used by the bacteria living at more than 1 kilometer below the surface to convert dissolved inorganic carbon into energy.
- This is an ecosystem that can exist without sunlight or organically processed carbon. The bacteria exist completely independent of

surface life. This ecosystem is referred to as being autotrophic, which means that it does not need organic sources of carbon to survive.

- Bacteria like this would probably survive a great asteroid impact because their survival is not predicated on the Earth's surface viability.
- Other strange life-forms use the following:
 - Sulfate-based bacteria: H_2SO_4 (sulfate) + 4H_2 (hydrogen gas) $\rightarrow \text{H}_2\text{S} + 4\text{H}_2\text{O}$.
 - Methanogenic bacteria: $\text{CO}_2 + 4\text{H}_2 \rightarrow \text{CH}_4 + 2\text{H}_2\text{O}$ or $4\text{CO} + 2\text{H}_2\text{O} \rightarrow \text{CH}_4 + 3\text{CO}_2$.
 - Acetylene-based bacteria: $2\text{CO}_2 + 4\text{H}_2 \rightarrow \text{CH}_3\text{COOH} + 2\text{H}_2\text{O}$.
 - Iron-reducing, or hydrogen-oxidizing, bacteria: $2\text{Fe}^{+3} + \text{H}_2 \rightarrow 2\text{Fe}^{+2} + 2\text{H}^+$.
- An interesting example of an iron-reducing, or hydrogen-oxidizing, bacteria is the hyperthermophilic species, which thrive in extremely hot environments, such as 80°C to 125°C water. They can be found at mid-ocean vents or in hot springs (such as the ones in Yellowstone, Wyoming)—both of which are locations that are associated with past or recent volcanic activity.
- The bacteria that live in mid-ocean spreading areas get their carbon from the seawater, but their major source of energy is the atmospheric CO₂ that has dissolved in the oceans. The CO₂ is from inorganic sources; photosynthesis is not used. The bacteria in this environment are thus referred to as chemoautotrophs.
- The bacteria that live in hot springs, such as the ones in Yellowstone National Park, display themselves in vivid colors. These bacteria are photosynthetic.

- Another example of life in a very hostile environment is the microbes living in the harsh valleys of Antarctica, which is a frozen desert where water is scarce. Here, bacteria live in rocks, which absorb sunlight when it's available and provide small amounts of water to the bacteria—called lithoautotrophs because they reside in rock and utilize CO₂ from the atmosphere.
- A final example of life surviving in solid rock is the cyanobacteria that live just a few millimeters below the surface of transparent rock in the harsh Atacama Desert of Chile. These bacteria can survive super droughts inside the rock. There are current scientific claims that some microbes can survive for over a million years in salt rocks from the desert, just waiting to have liquid water to go back to living again.
- These examples of life thriving in harsh conditions may seem unusual, but they are thought to be the norm compared to the first life on Earth. The kinds of life we are most familiar with, such as our pets or ourselves, are not standard; they are an evolution away from the standard, or original, form of life, such as the hyperthermophilics.
- It has been estimated that there are more than 10³⁰ microbes on Earth (from bacteria alone). If each is 1/1,000,000 of a meter (1 micron), then if we placed each side by side, we would have a line about 10²⁴ meters long. Note that a galaxy is 10⁵ light-years × 10¹⁶ meters per light-year = 10²¹ meters, so that line of microbes would be approximately 1000 galaxies long.



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In addition to being photosynthetic, many species of cyanobacteria can transform gaseous nitrogen into compounds that can be used by living cells.

How Life Stores Information

- One of the most marvelous things about life is how complex it is. There are approximately 100 trillion cells in a human being, and each cell contains 6 billion base pairs of genetic information. That is a lot of information to pass from cell to cell as cells divide, so life needs a complex molecule that can store a lot of information and reproduce it without error—or almost without error.
- The secret to terrestrial life is DNA. Due to its double helix structure and its nucleotide pairs (C to G and A to T), it can always make a copy of itself if it is split down the middle.
- RNA is the companion molecule to DNA; it is, however, single-stranded (uses U instead of T). RNA copies information from DNA (mRNA), decodes the mRNA, builds proteins (tRNA), and helps build ribosomes (rRNA). RNA autocatalytic ribosomes may have played a central role in early prokaryotic life.
- It is interesting to note that there are no real exceptions to the rules that we have found for all life on Earth. There is proof that life might have started on the Earth in as little as 100 million years. This is a very short time if you compare it to the fact that it took at least 10 times longer to have complex eukaryotic cells. How could simple life appear in less than 100 million years but take more than 1000 million years to evolve?
- In the 4.5-billion-year history of the Earth, there must have been a time when life was able to start again—from scratch. We basically expect there to be a chance that a life-form with different DNA and RNA could have arisen, but despite plumbing the depths and looking in strange places like California’s Mono Lake, no definitive sign of “strange life” has been found.

The Tree of Life

- Sometimes there is an error in the reproduction of the DNA. This reflects just slightly different rRNA sequences. These errors—if minor—are passed down from generation to generation. We can

now track how similar different forms of life are by simply looking at how similar their rRNA sequences are.

- All animals are close genetically, but animals and bacteria are far away from each other genetically. The universal ancestor branched off into two domains: Bacteria and Archaea.
- On the so-called tree of life, we see that the Eukarya (cells containing nuclei) domain, which includes animals, diverged from the Archaea domain. All of the species that are closest to the root of the tree of life—the universal ancestor—are hyperthermophilic in nature.
- The norm for the first life—at least the surviving universal ancestor—on Earth may have been hyperthermophilic, and the origin was likely in a CO₂ atmosphere.
- Today, life can exist in many different environments. Organisms are creative in their use of available energy. In order to understand how and where life could develop in the cosmos, we must look for all the different kinds of energy sources available. We must also follow the liquid water because that is the key to all terrestrial life as well.

Suggested Reading

Bennett and Shostak, *Life in the Universe*.

Irwin and Schulze-Makuch, *Cosmic Biology*.

Jakosky, *The Search for Life on Other Planets*.

Kaufman, *First Contact*.

Plaxco and Gross, *Astrobiology*.

Questions to Consider

1. How long do you think we could live on Earth if all the microbes died? On the other hand, would microbes even notice if mankind disappeared?
2. Why do you think that biologists have only found life directly related to us? Why couldn't a slightly different “strange life” arise independently on Earth?

Origin of Terrestrial Life

Lecture 8

We now understand what life needs on Earth, and we also know that Earth started out devoid of life, so an obvious question is: Where did the life on Earth come from? How did nonliving matter give rise to living matter? In this lecture, you will learn that this is in no way a trivial question to answer. There is great mystery surrounding the origins of life, formally known as biogenesis, and this lecture will provide some of science's best guesses for how life might have come about.

The Definition of Life

- A generally acceptable definition of life that works fairly well is: “Living entities utilize energy from some source to drive chemical reactions; they are generally capable of reproduction and can undergo some degree of evolution.”
- Organisms on Earth utilize chemical reactions—equations of life—in various ways to derive energy for building proteins, growing, and other functions. In addition, reproduction is essential for any living thing to matter. Finally, if a life-form cannot undergo evolution, then it is also not going to survive in the long term, although the rate of this evolution can be very slow.
- Obviously, this is not a perfect definition for all life on Earth. Exceptions include mules, which are a cross between horses and donkeys and cannot reproduce—yet are clearly alive. In addition, viruses are typically not thought of as alive; they lack the machinery to reproduce their own DNA without the help of other cells—yet they meet the definition for life.
- Some bacteria have not undergone serious evolution for 3.5 billion years—yet are alive. There are also things like desert varnish, a black lichen on rocks in the desert that slowly builds up as the bacteria that live on the rock give off waste as they use magnesium for life.

- The prerequisites for life on Earth are liquid water and energy. The basic building blocks of organic molecules are carbon (C), hydrogen (H), oxygen (O), nitrogen (N), phosphorus (P), and sulfur (S).
- Carbon is really the key element. It forms a wider variety of chemical bonds than any other element and is present in all of the biological chemicals. All life may be based on carbon.
- To build proteins, amino acids are needed. There are 20 standard amino acids for life on Earth.
- Some method of passing on genetic information—a reproduction mechanism—is needed to sustain life. For early life, simple molecules would have been used in the construction of more complex organic molecules. Today's DNA/RNA system is too complex to have been used at the start of life on Earth.
- Today, chemical or sunlight energy is available and utilized. In early life, chemical energy was probably used because it is simpler than the utilization of sunlight.

The Miller-Urey Experiment

- The Miller-Urey experiment is the classical experiment on the origin of life. It was a laboratory experiment that was conducted in the 1950s to simulate the hypothetical conditions on early Earth.
- Taking molecules believed to represent the major components of Earth's early atmosphere, Stanley Miller and Harold Urey put CH_4 (methane, a reduced form of carbon), NH_3 (ammonia), H_2 (hydrogen), and H_2O (water) in a closed loop system.
- A flask was partly filled with liquid water, gaseous methane, hydrogen, and ammonia. The flask was heated, and water vapor was created. The energy source was an electric spark, which was meant to simulate lightning storms believed to be a common occurrence on early Earth.

- In this experiment, chemical reactions created were recycled (condensed) back into the liquid water. The experiment was repeated for several weeks. The analysis of the flask contents revealed a wide variety of important organic molecules, including amino acids. A sixth of the carbon had turned into organic molecules—with the amino acid accounting for about 2 percent of the carbon atoms.
- In the 1950s, these results were so promising that many believed scientists were on the verge of creating life in the lab, but in the 21st century, we are still very far from such an ability.
- We have made breakthroughs in genetics. Scientists have had some success in the field of synthetic biology in “designing” simple single-celled microbes, but this involves using the existing mechanisms of life.
- More precisely, slightly different bacteria can be created today by slightly modifying the genome of existing life, as shown by the work of the J. Craig Venter Institute. This is definitely not creating truly new life—nor is it done from abiotic, or “dead,” components, so we are no closer to creating life.
- The problem with the Miller-Urey scenario is that the atmospheric ammonia and methane, which are crucial to the process, would not have been stable in the early terrestrial environment. The methane and ammonia would have broken up eventually, and the hydrogen would have escaped from the atmosphere, resulting in the reducing atmosphere becoming more oxidizing. In a nonreducing atmosphere (containing less hydrogen and more oxygen), it was much harder to produce significant amino acids—but it still works.

Formation of Autocatalytic Monomers/Polymers

- Organic molecules can be created by nonbiological methods, such as hot springs and chemistry (the Miller-Urey experiment), but how do we make “living” molecules from “nonbiological” building blocks?

- It is thought that early life on Earth was an RNA-based life because it is simpler than DNA. We usually need DNA/RNA to make proteins, which in turn are needed with enzymes to build more DNA/RNA.
- How could we have had an RNA world without the proteins to make the RNA—which is impossible because the proteins need the RNA to be made? RNA cannot reproduce itself without the catalytic activity of the enzymes, and the enzymes are contained within the RNA.
- Autocatalytic RNA molecules, or ribozymes, were discovered. They can by themselves act as enzymes and facilitate the production of new RNA molecules, so they are both RNA and enzymes. Some viruses still only use RNA, perhaps like early life did.
- Ribozymes may be related to earlier life-forms before complex DNA molecules. However, these ribozymes could not have been created by chance out of a primordial soup of amino acids. Even the simplest RNA molecule is very complex and could not be assembled randomly.
- It is probable that ribozymes supplanted an even simpler molecule that still contained genetic information and could reproduce. This molecule may have been a simple polymer constructed by linking together simple molecules, which is what DNA and RNA really are.
- There are some scientists who think that RNA is way too complex to reproduce in prebiotic conditions and would need a great deal of help to arise from a soup of random polynucleotides. Indeed,



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Deoxyribonucleic acid (DNA) was first discovered in 1869.

we cannot expect such complex polymers to arise from a random combination of building blocks.

- While we have no idea how the first living molecules formed in detail, science offers some guesses.
 - Dehydration reaction: In a dehydration reaction, a polymer is created by dehydration (the release of a water molecule). This type of reaction occurs in environments with minimal amounts of water, such as shallow-water tide pools or in warm and relatively dry environments.
 - Inorganic template: This approach involves a nonbiotic template, or jig, that simulates the RNA's own template. Pyrite and montmorillonite clay have been suggested as possible inorganic templates. Lab experiments show that the clay can produce complex RNA-like molecules. In free water, they will eventually dissolve complex structures, but between two clay layers, molecular adhesion forces could produce a long polymerized strand of nucleotides.
 - Stringing together nucleosides: Nucleosides—which are closely related to nucleotides, the building blocks of RNA and DNA—might have been strung together. However, the right conditions to create the nucleosides, consisting of both purine (A and G) and pyrimidine (C, T, and U) nucleosides, are very specific and probably did not apply to prebiotic Earth. The prebiotic conditions seem to be only right for the creation of purine nucleosides. Perhaps earliest life used only the purines to pass on genetic information and the pyrimidines were added later. This approach is more like a dream because of the unlikely nature of an RNA-like polymer emerging from a soup of nucleosides.

Formation of Membranes

- Cellular life needs a membrane to enclose the RNA and DNA in the cell. The membrane allows the cell to keep its RNA and DNA

together and distinct from other cells. The membrane cannot dissolve in water but must be permeable.

- The heating of various organic polymers can form organized clusters that enclose organic molecules. However, modern cell membranes are not like either of these. The transition between the early and modern membranes is not understood.
- We now understand what was needed from the first life on Earth: organic molecules (such as amino acids) with hydrogen, oxygen, nitrogen, phosphorus, and liquid water. We know that these were common, but we do not really understand how the first living, reproducing, evolving polymer came to be. Once this autocatalytic polymer came to be, it must have been encased in a membrane to produce the first primitive (prokaryotic) cell.
- We do not yet understand the origin of life. However, all of the necessary building blocks were present. We understand some of the steps necessary to create life, but there are gaps in our knowledge. However, life did develop quickly and, from there, evolved rapidly, leading to the conclusion that life is robust.

Suggested Reading

Bennett and Shostak, *Life in the Universe*.

Irwin and Schulze-Makuch, *Cosmic Biology*.

Jakosky, *The Search for Life on Other Planets*.

Kaufman, *First Contact*.

Plaxco and Gross, *Astrobiology*.

Questions to Consider

1. Clearly, the chemistry to start life is complex: Witness our complete lack of success in forming anything remotely lifelike from nonliving components. How do you think life might have started on Earth?
2. Why do we think that our universal common ancestor was likely a hot-water-loving extremophile?

Astrobiology—Life beyond Earth

Lecture 9

Life beyond the Earth would have some similarities to life on Earth but would be completely alien in other aspects. In this lecture, you will learn that in general, the most basic things that life in our universe require are a liquid solvent (water is an excellent candidate, but it is possible that other forms of life could use other solvents); a strong presence of the elements that are necessary for relevant biochemical reactions, such as metabolism and reproduction (most researchers agree that carbon is likely the keystone element to life); an energy source for life (a vast range is possible throughout the cosmos), and a stable environment (with few impacts).

Universal Requirements for Life in Our Universe

- While we have a range of life-forms on Earth, there is a list of properties that are common to all life-forms. This list will help guide our efforts in understanding where to look for life in our universe.
- In general, terrestrial life needs liquid water; the presence of the elements that are necessary for relevant biochemical reactions (metabolism and reproduction), including carbon, hydrogen, oxygen, nitrogen, phosphorus, and sulfur; an energy source; and a stable environment (one with few impacts, for example).
- Liquid water is very important because no life on Earth is possible without it. It is a solvent for most molecules. It is, in fact, almost too good at dissolving organic molecules—hence the need for cellular membranes.
- Water is liquid at a large range of temperatures (0°C to 100°C, or 32°F to 212°F). The upper temperature limit is closest to the highest temperature at which complicated organic molecules can survive.

- Earth is very special in that it is relatively near the triple point for water. The triple point is a point in pressure and temperature space at which an element can exist as a solid, a liquid, and a gas. For example, it is possible to see an iceberg (solid) floating on water (liquid) during a foggy day (gas).
- The fact that icebergs float is really surprising. The solid form—ice—floats rather than sinks, thereby creating a blanket on top of the remaining liquid, preventing it from freezing solid. This allows species living below the surface to survive when the temperatures drop below freezing.
- Water is a polar molecule, and long hydrocarbons such as oil or cell membranes, which are nonpolar, will not dissolve in it. This helps us understand why ice floats.
- Water has an unsymmetrical molecule. Oxygen has six valence electrons, which means that it needs two more electrons to fill its outer shell, so it shares two electrons from two hydrogen molecules—the gain of two electrons gives eight to fill the outer shell of the oxygen—and four other oxygen electrons stay on the other side (making two pairs), leading to the hydrogen molecules being on the other side about 104.5 degrees apart.
- All of the electrons spend 90 percent of their time closer to the oxygen, so it is slightly negative, and the hydrogen becomes slightly positive.
- Hydrogen bonds allow ice molecules to be less dense than liquid water. Icebergs have approximately 9 percent of their mass above water because the hydrogen bonds make ice about 9 percent less dense than water.
- We might find that in some worlds, there are other liquids available—but no water. For example, Titan, a moon that revolves around Saturn, is far too cold for liquid water, but its conditions are right for liquid methane or ethane. Ammonia (NH_3), methane (CH_4) and

ethane (C_2H_6) are all possible candidates, but none of these remains a liquid above $-33^{\circ}C$, which means a lack of hydrogen bonds.

- At such low temperatures, the chemical reactions of life would be too slow to be completed in the time of the Earth's age. Hence, we know that these alternative liquids were not the breeding grounds for life on Earth. However, they may act as breeding grounds on other planets.
- There are lower-mass stars that live much longer than the Sun and would remain stable for long enough for life to evolve even at much slower rates—or colder temperatures. Because of their nonpolar nature, however, Earthlike membranes made of nonpolar molecules would dissolve in these kinds of liquids.
- If life exists on other planets in the presence of these liquids—ammonia, methane, and ethane—then it would be completely different chemically from life on Earth.

Silicon Life

- Silicon is located right under carbon on the periodic table. Silicon is capable of forming long carbon-like chains; it is also abundant in the Earth's crust.
- However, silicon cannot form double bonds like carbon can. As a result, carbon can combine with two oxygen atoms to form CO_2 . This is important because, then, carbon can exist as a gas as well as dissolve in water. This ability to move through the atmosphere and oceans means that carbon is readily available to organisms.
- The structure of SiO_2 is very different from that of CO_2 ; SiO_2 exists as a latticelike network made up of single bonds (each is individually an SiO_4 molecule, but the oxygen atoms are shared, leading to a net chemical formula of SiO_2) rather than as individual atoms. Silicon dioxide—sand—is solid at temperatures well above the boiling point of water. This life would have to breathe out sand.

Periodic Table of Elements

1 H	Hydrogen 1.0079	4 Be	Boronium Beryllium 4.00265
3 Li	Lithium 6.941	5 B	Boron 10.881
11 Na	12 Mg	6 C	Carbon 12.0107
Sodium 22.9897	Magnesium 24.3059	7 N	Nitrogen 14.0067
19 K	20 Ca	8 O	Oxygen 15.9994
Potassium 39.096	Calcium 40.078	9 F	Fluorine 18.9984
37 Rb	39 Sr	10 Ne	Neon 20.1797
Rubidium 85.4678	Samarium 87.672	11 He	Helium 4.00265
55 Cs	56 Ba	12 C	Carbon 12.0107
Ceesium 132.9055	Barium 137.327	13 Al	Aluminum 26.9815
87 Fr	88 Ra	14 Si	Silicon 28.0855
Francium (223)	Radium (226)	15 P	Phosphorus 30.9738
57 La	58 Ce	16 S	Sulfur 32.065
Lanthanum 138.9055	Cerium 140.116	17 Cl	Chlorine 35.453
89 Ac	90 Th	18 Ar	Argon 39.948
Actinium 227.031	Thorium 232.0381	19 F	Fluorine 18.9984
5 B	6 C	20 Ne	Neon 20.1797
13 Al	14 Si	21 O	Oxygen 15.9994
31 Ga	32 Ge	22 N	Nitrogen 14.0067
33 As	34 Se	23 F	Fluorine 18.9984
35 Kr	36 Br	24 Ne	Neon 20.1797
37 Xe	38 Br	25 Ar	Argon 39.948
39 Lu	40 Ti	26 Fe	Iron 55.845
40 Sr	41 V	27 Mn	Manganese 54.938
41 Y	42 Cr	28 Co	Cobalt 59.932
42 Zr	43 Ru	29 Ni	Nickel 58.6934
43 Nb	44 Rh	30 Cu	Copper 63.546
44 Mo	45 Os	31 Zn	Zinc 65.409
45 Ru	46 Pd	32 Ga	Gallium 69.723
46 Cd	47 Ag	33 Ge	Germanium 74.9216
47 Rh	48 Pd	34 As	Arsenic 78.56
48 Pt	49 In	35 Se	Selenium 79.904
49 Rhodium	50 Sn	36 Br	Bromine 79.904
50 Cd	51 Te	37 Cl	Chlorine 35.453
51 Cd	52 Te	38 Ar	Argon 39.948
52 Te	53 I	39 Ne	Neon 20.1797
53 Iodine	54 Xe	40 Kr	Krypton 83.798
54 Xe	55 Te	41 Ar	Argon 39.948
55 Te	56 Po	42 Kr	Krypton 83.798
56 Po	57 At	43 Ar	Argon 39.948
57 At	58 Rn	44 Kr	Krypton 83.798
58 Rn	59 Lu	45 Ar	Argon 39.948
59 Lu	60 Tb	46 Kr	Krypton 83.798
60 Tb	61 Dy	47 Ar	Argon 39.948
61 Dy	62 Ho	48 Kr	Krypton 83.798
62 Ho	63 Er	49 Ar	Argon 39.948
63 Er	64 Tm	50 Kr	Krypton 83.798
64 Tm	65 Ho	51 Ar	Argon 39.948
65 Ho	66 Dy	52 Kr	Krypton 83.798
66 Dy	67 Ho	53 Ar	Argon 39.948
67 Ho	68 Er	54 Kr	Krypton 83.798
68 Er	69 Tm	55 Ar	Argon 39.948
69 Tm	70 Yb	56 Kr	Krypton 83.798
70 Yb	71 Lu	57 Ar	Argon 39.948
71 Lu	72 Erbium	58 Ar	Argon 39.948
72 Erbium	73 Ytterbium	59 Ar	Argon 39.948
73 Ytterbium	74 Lutetium	60 Ar	Argon 39.948
74 Lutetium	75 Hafnium	61 Ar	Argon 39.948
75 Hafnium	76 Ta	62 Ar	Argon 39.948
76 Ta	77 W	63 Ar	Argon 39.948
77 W	78 Re	64 Ar	Argon 39.948
78 Re	79 Os	65 Ar	Argon 39.948
79 Os	80 Au	66 Ar	Argon 39.948
80 Au	81 Hg	67 Ar	Argon 39.948
81 Hg	82 Pb	68 Ar	Argon 39.948
82 Pb	83 Bi	69 Ar	Argon 39.948
83 Bi	84 Po	70 Ar	Argon 39.948
84 Po	85 At	71 Ar	Argon 39.948
85 At	86 Rn	72 Ar	Argon 39.948
86 Rn	87 Radon	73 Ar	Argon 39.948
87 Radon	88 Thorium	74 Ar	Argon 39.948
88 Thorium	89 Protactinium	75 Ar	Argon 39.948
89 Protactinium	90 Uranium	76 Ar	Argon 39.948
90 Uranium	91 Neptunium	77 Ar	Argon 39.948
91 Neptunium	92 Plutonium	78 Ar	Argon 39.948
92 Plutonium	93 Americium	79 Ar	Argon 39.948
93 Americium	94 Curium	80 Ar	Argon 39.948
94 Curium	95 Bk	81 Ar	Argon 39.948
95 Bk	96 Cf	82 Ar	Argon 39.948
96 Cf	97 Es	83 Ar	Argon 39.948
97 Es	98 Fm	84 Ar	Argon 39.948
98 Fm	99 Md	85 Ar	Argon 39.948
99 Md	100 No	86 Ar	Argon 39.948
100 No	101 Lr	87 Ar	Argon 39.948
101 Lr	102 Lu	88 Ar	Argon 39.948
102 Lu	103 Lawrencium	89 Ar	Argon 39.948
103 Lawrencium	104 Francium	90 Ar	Argon 39.948
104 Francium	91 Radium	92 Ar	Argon 39.948
91 Radium	93 Barium	94 Ar	Argon 39.948
93 Barium	95 Calcium	96 Ar	Argon 39.948
95 Calcium	97 Potassium	98 Ar	Argon 39.948
97 Potassium	99 Sodium	99 Ar	Argon 39.948
99 Sodium	100 Lithium	100 Ar	Argon 39.948
100 Lithium	101 Hydrogen	101 Ar	Argon 39.948

- Silicon cannot exist as a gas on Earth—nor does it dissolve in water in adequate quantities—so it cannot be easily be used in reactions of life.
- Finally, silicon bonds are weaker than carbon bonds, making silicon compounds somewhat less stable. Silicon is also more than 10 times less abundant in the universe than carbon.
- While silicon-based life has been a favorite for science fiction stories, not many scientists share this enthusiasm. The longest natural molecules with silicon are just six atoms. This includes meteorites as well.
- The most likely form of silicon-based “life” might be some sort of artificial intelligence from a partially silicon-based computer, but that’s not really silicon-based life. Most scientists doubt that silicon-based life can work chemically; only carbon seems to have a chance at the complex chemistry required.

Energy Sources and Stability

- Extraterrestrial life will certainly need to utilize an energy source to survive. Metabolizing organic molecules results in chemical energy. These organic molecules can form abiotically from heating due to lightning or hydrothermal systems—or they can come from space dust and meteorites.
- Metabolizing H_2S and H_2 is also possible in rock or at hot vents on the ocean floor. In addition, alien life can possibly use a variant of photosynthesis, where the energy source is the Sun. There may be others that we do not have very much experience with on Earth, including lightning energy, geothermal energy, and many different potential energy sources on other planets.
- Life needs a stable environment to develop and survive. The impact rate must be low. In our own solar system, the gravitational pull of outer planets, such as Jupiter and Saturn, have acted as comet and meteorite blockers (after a brief period of late heavy bombardment).

Now, these planets absorb more impacts than send to Earth, so maybe it helps to have circular giant outer planets for a stable inner terrestrial world like Earth.

- In addition to impact rate, life needs protection from ultraviolet (UV) radiation to be stable. Wavelengths under 0.3 microns destroy any organic molecules, so DNA-like polymers would have to have a very robust self-repair to survive.
- The fact that clothes fade in the Sun is an example of direct UV damage from the Sun. Even the UV radiation that gets through the Earth's atmosphere can be quite good at cutting apart the long dye molecules used to color clothes.
- Presently, ozone (O_3) protects the Earth. On early Earth, a very thick atmosphere would have helped to protect life—plus, living in a shallow layer of dirt or water would have helped. Another possibility would be a subsurface ocean, such as might exist on Jupiter's moon Europa.

Suggested Reading

Bennett and Shostak, *Life in the Universe*.

Dick, *The Living Universe*.

Impey, *The Living Cosmos*.

Irwin and Schulze-Makuch, *Cosmic Biology*.

Kaufman, *First Contact*.

Plaxco and Gross, *Astrobiology*.

Questions to Consider

1. Why is water ice's ability to float so important for life?
2. Why do most astrobiologists believe that carbon chemistry is likely universal to all life in our universe?

Has Mars Always Been Dead?

Lecture 10

Mars is an incredibly important planet in our solar system for the search for life in our universe. Mars is too small (1/10th the Earth's mass) and too far from the Sun (50 percent farther than the Earth) to be warm enough to be habitable on its surface today. However, there is clear evidence that Mars likely was warmer in the distant past. In fact, Mars has been NASA's first priority for the search for exolife. In this lecture, you will learn why Mars is so interesting and what the search for life on Mars has found to date.

Facts about Mars

- Mars has the following in common with the Earth: volcanism (in the past), tectonics (without plates, in the past), wind erosion, water erosion, impacts, and icy poles. All of this points to Mars possibly having life now (or more likely in the past), but Mars is quite different from the Earth as well.
- Mars is cold. It has an average temperature of 220 K (-53°C or -63°F) but is above 0°C at its equator in the summer. Mars also has a thin atmosphere. Its atmosphere is approximately 6 mbar while the Earth's atmosphere is 1010 mbar, so Mars's atmosphere is just 0.5 percent of the thickness of Earth's.
- Mars's atmosphere is mainly CO₂ while the Earth's atmosphere is mainly O₂ and N₂. In the Earth's atmosphere, CO₂ is only 0.3 mbar, but that number is rising. Mars is just 10 percent the mass of Earth and just half the size of Earth.
- The key problem is that Mars doesn't have enough of an atmosphere to be warm enough and have enough gas pressure to have stable liquid water on its surface—it simply sublimates away (or freezes solid) as soon as it is exposed to the thin Martian atmosphere. At no point can it be a liquid, even in the warmest parts of the surface.

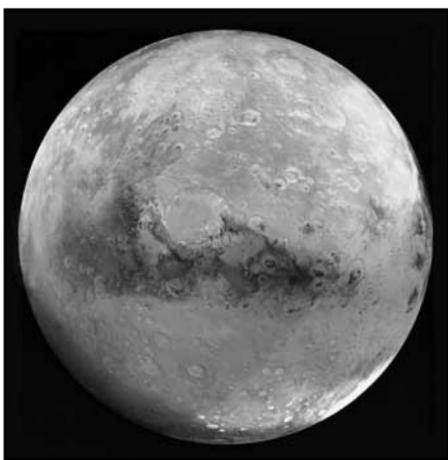
The Solar Constant

- Light leaves the Sun as an ever-expanding sphere. The area of a sphere is $A = 4\pi D^2$, so the power received divided by the surface area on Earth, where $D_{\text{Earth}} = 1$ astronomical unit (AU), is called the solar constant: L_{Sun}/A .
- The power received on a 1-meter patch of ground is $P_{\text{Earth}} = L_{\text{Sun}}/4\pi D^2 = (3.8 \times 10^{26})/(4\pi(1.5 \times 10^{11})^2) = 1.3$ kW (kilowatts) falling on a 1-by-1-meter patch of Earth. (It varies around this value by 7 percent because the Earth is slightly closer to the Sun in December and farther from the Sun in June.) P varies as $1/D^2$, which is the inverse square law.
- The reason Mars is so cold (besides a lack of greenhouse from its weak atmosphere) is the fact that it is $D = 1.5$ AU from the Sun. On Mars, $P_{\text{Mars}} = P_{\text{Earth}} (1/1.5)^2 = 0.6$ kW, which is only 44 percent that of the Earth, so Mars's surface is much colder than the Earth's.
- Interestingly, a Martian day is 24.6 hours (very close to that of Earth). It has a much longer year (686 Earth days), which is because the length of a “year” varies as $D^{3/2}$. It has similar tilt as Earth with its 25-degree tilt (compared to 23.5 for the Earth).
- Overall, the seasons last for twice as long and are, therefore, harsher on Mars. However, because Mars is closer to the Sun in the southern summer, the south has very “hot” (above freezing) summers while the northern hemisphere has “milder” seasons that rarely rise above freezing. Water ice at the poles never melts, but CO₂ does sublimate in the summer and forms frost in the winter.

Water on Mars

- Mars has lots of water. Every modern NASA mission to Mars has found evidence of water on Mars, but it is all either frozen or vapor forms. Liquid water (the key to life) is not stable at the very low pressures on the surface. For the most part, just below the surface on Mars, the temperatures are even colder, so the water ice is still ice.

- The University of Arizona, along with Ball Aerospace & Technologies Corp., built an amazing 0.5-m telescope called HiRISE (High Resolution Imaging Science Experiment) camera on NASA's *Mars Reconnaissance Orbiter*. This is the most powerful camera (which is really a full telescope) ever sent to study the planets of our solar system. HiRISE can resolve objects as small as 1 meter (3 feet) across on the surface of Mars.
- University of Arizona Professor McEwen, et al., reported in the August 2011 issue of *Science* that there are “warm season” (250 K to 300 K) temporary features that present themselves as possible briny liquid water running down the side of steep (40-degree) canyon walls.
- While not a common sight on Mars, these can be seen by the hundreds in the right places at the right times. This is widely believed to be the best evidence that some form of liquid water can exist near the surface of Mars—even today—albeit for a very short period of time.
- The University of Arizona and Jet Propulsion Laboratory (JPL)/NASA landed a lander in the northern “arctic plains” region of Mars in 2008. The lander confirmed that it landed on dirt covering water ice. It used its arm to dig a trench, in which water ice (white) was clearly visible. Then, over 4 days, the water ice



Mars is the fourth planet from the Sun in the solar system and is ranked seventh in size and mass.

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sublimates away, but there is no liquid state—it appears to directly turn to vapor.

Was Mars Warmer and Wetter in the Past?

- All past landers have found no signs of organics on the surface of Mars. The Mars atmosphere is too weak to block the UV from the Sun. Therefore, today, the surface of Mars is sterilized and devoid of life. However, in the past, was Mars a more habitable world?
- The ancient Mars climate is thought to be more capable of supporting liquid water at or near its surface. This conclusion is supported from evidence that estimates a substantial fraction of Mars's surface to be older than 3.5 billion years—meaning that since that time, erosion (water, for example) has been rare.
- We see signs that erosion was 1000 times greater for rocks older than 3.5 billion years on Mars. Smaller impact craters are not present (destroyed), and big impact craters appear eroded. In contrast, younger rock has not been altered significantly. After 3.5 billion years, liquid water left the surface of Mars. This older rock erosion looks like water erosion.
- Ancient Mars may have had a very thick CO₂ greenhouse atmosphere that made the huge volcanoes there (like early Earth), which allowed liquid H₂O to be present on the surface. Even though the young Sun was weaker (about 20 percent less bright) than it is today, massive floods seem to have occurred throughout Martian history.
- Flooding stems from beneath the surface, indicating that water was trapped in the Martian subsurface. Subsurface geothermal heating melts ice; perhaps liquid water existed (exists?) only a kilometer or two beneath the surface.
- Just like on Earth, volcanoes on Mars would outgas H₂O. The shield volcano Olympus Mons is 25 kilometers high with an 80-kilometer caldera—which is 100 times larger than that of Mauna

Loa, Hawaii—making it the largest extinct volcano in the solar system. Today, Mars doesn't appear to be volcanically active, but it was active as recently as 180 million years ago, and it may still be active.

- Early Mars may have been very similar to early Earth, including having liquid water on the surface, a thicker CO₂ atmosphere, above-0°C temperatures, a hot core and volcanoes, a protective magnetic field, and hot springs and vents. In fact, Mars may have been “habitable” from approximately 4 to 3.5 billion years ago.
- Because Mars is still hot (but not molten) in its interior, at 1 to 2 kilometers below the surface, ground ice would melt. Therefore, microbes like those living in the Columbia River Basalts could survive by using hydrogen gas (released from reactions between rock and water). We can look for methane gas, which could be a waste gas from subsurface life on Mars.

Methane Gas on Mars

- Since 2003, there have been reports of methane gas on the surface of Mars. None of the space-based spectrographs have high enough spectral resolution to clearly detect these features, but ground-based spectrographs are much more advanced than those in space. Coupled with large ground-based telescopes, we have mapped where on the surface of Mars the methane is coming from.
- In 2009, NASA released ground-based images that showed significant amounts of methane gas “plumes” that suggested Mars “was not dead.” This, in turn, was reported as NASA finds life on Mars. However, NASA scientist Michael Mumma could not know if these plumes are due to geology or biology. In fact, these methane signals seem to have disappeared of late.
- Moreover, a recent paper in *Nature* claims that these plumes can be explained by UV radiation on relatively new meteorites on the Mars surface. Scientists can make CH₄ from meteorites on Earth by exposure to UV.

- A meteor falls on Mars, and then the carbon in the meteorite is exposed to UV, causing methane to be released in the atmosphere and then disappear. Hence, there is no need for life on Mars.
- The variable locations and quick (months) disappearance of this methane is very troubling to many planetary scientists. Indeed, there is not enough free oxygen in Mars's atmosphere to remove all of the methane as fast as was observed.
- Some scientists instead note that the observations may be flawed because the measurements from the ground are badly contaminated by Earth's own methane, which needs to be modeled and subtracted off.

Suggested Reading

Bennett and Shostak, *Life in the Universe*.

Irwin and Schulze-Makuch, *Cosmic Biology*.

Kaufman, *First Contact*.

Pyle, *Destination Mars*.

Questions to Consider

1. Why do we spend so much time sending missions to Mars and not to the closer planet Venus?
2. Do you think that Mars's warmer and wetter past could have allowed Martian life to exist for a short period?

Evidence for Fossilized Life from Mars

Lecture 11

A meteorite from the ancient highlands of Mars shows that complex carbon chemistry occurred on the surface of Mars in the distant past, but the claim that microfossils are seen in the rock is controversial. The scientific community, while respecting the work of David McKay et al., have largely dismissed the claims of life from Mars in the rock. It is just not possible to remove all doubt that all of the features were terrestrial in nature. In this lecture, you will learn that the evidence is simply not extraordinary enough.

Martian Meteorite

- August 7, 1996, is often claimed to be the modern start of the field of astrobiology. On that day, NASA claimed to have found evidence of past life on Mars.
- The evidence was based on a detailed analysis of a meteorite known as ALH 84001. At just 1.9 kilograms, it looked like a normal meteorite. In fact, it looked so normal that it was not immediately recognized for what it was: a Martian meteorite.
- Scientists are fairly confident that it comes from Mars because its abundances of oxygen 16, oxygen 17, and oxygen 18 are very different from Earth rocks. It was found in the Antarctic, which is a particularly good place to find meteorites because they are relatively easy to identify—they fall on vast sheets of ice that flow up against the mountains.
- ALH 84001 is distinct from the other known Martian meteorites, which are composed of young volcanic basalt. ALH 84001 is composed of almost pure pyroxene, which is one of the first materials to solidify from an originally molten planet. ALH 84001 is from the ancient Martian highlands, where there might have been liquid water in the past.

- NASA scientists David McKay and Everett Gibson examined ALH 84001 for evidence of fossilized life, which would be contained in the carbonate material that was deposited within the rock about 1.8 to 3.6 billion years ago.
- The meteorite was realized to be very precious and was very carefully examined. Very small fossil life was found in carbon-rich globules of the meteorite with electron microscopes.
- To show that shapes could really be fossil bacteria, McKay and coworkers have tried to show the following:
 - The bacteria shapes are actually the sizes and shapes of known living organisms. (However, they were really very much smaller than typical bacteria).
 - The bacteria shapes are really part of the rock and were not produced accidentally while they prepared the sample for study. (This seems to be agreed.)



The landmass of Antarctica is almost completely covered by an immense sheet of ice.

- The bacteria shapes are not Earth bacteria that somehow wiggled into ALH 84001 while it was in Antarctica. (There is now evidence that, indeed, some of these samples have been contaminated during the 13,000 years that the rock was sitting in Antarctica.)
- In 2000, Steele et al. argued that portions of ALH 84001 were infested with terrestrial bacteria. The chips examined showed that the outer layers were full of rock-eating microbes from Earth, which were attracted to the carbon (food) deposits that were exactly where McKay et al. found all of their fossils.
- It turns out that almost all meteorites (even fresh falls) are contaminated with terrestrial life. On Earth, microbes are everywhere.

Mineral Grains and Organic Compounds

- Microscopic mineral grains are present in ALH 84001, some produced by living and fossil bacteria on Earth. McKay and coworkers suggest that these mineral grains in ALH 84001 may have been produced by Martian bacteria by arguing the following:
 - The mineral grains formed on Mars.
 - The mineral grains have chemical compositions, crystal structures, sizes, and shapes like biologically produced grains on Earth.
 - The different microscopic mineral grains and the larger mineral crystals they occur in are not likely to have formed by inorganic processes, without assistance from life.
- However, these same formations can be all explained by nonbiotic processes.
- Organic chemical compounds, or polycyclic aromatic hydrocarbons (PAHs), resemble the decay products of bacteria on Earth found in ALH 84001. PAHs in ALH 84001 include phenanthrene, pyrene,

chrysene, perylene or benzopyrene, and anthanthrene. Even more complicated PAH molecules are common on the Earth but are very rare in ALH 84001.

- McKay and coworkers argue that PAHs in ALH 84001 are derived from ancient Martian bacteria by trying to show that they are not contaminated from laboratory procedures. Furthermore, they contend the following:
 - They are not Earth PAHs that entered the meteorite while it was in Antarctica.
 - They are not like PAHs in other meteorites (which have nothing to do with life).
 - They are consistent with decomposition of simple bacteria.
 - They have a higher concentration of organic compounds in the inside of the meteorite than on the outside.
- The PAHs in ALH 84001 can all be produced by nonbiotic means. In fact, many are found in space. It is very interesting, but most scientists find this evidence lacking.
- McKay et al. made an extraordinary claim that they had proof of past life on Mars. After the initial claims, pieces of the meteorite were examined all around the globe. Some, such as Steele et al., found clear evidence that at least some of the meteorite was contaminated from Earth.

Panspermia

- The Mars meteor issue showed how rocks can be transferred from one planet to another—an idea called panspermia. This idea has some very dedicated adherents who believe that the cosmos is teeming with life.
- The basic idea of panspermia is that there are tons of interplanetary dust falling on the Earth every year (40,000 tons), which can be

traced by the very high helium 3 levels in interplanetary dust. The increased helium 3/helium 4 levels is, in part, due to exposure to the solar wind while in outer space.

- What would happen if even 1 percent of these interplanetary dust particles (and even interstellar dust) have some hearty microbes on them—or the much larger meteorites, such as the Mars meteorite landing on Earth packed with dormant life? The Earth would be constantly bombarded with life from outer space.
- It is now generally agreed that the new classes of extremophiles show that extreme life is much heartier than we could have imagined 15 years ago. For example, there are microbes that can be desiccated for millions of years in salt rocks and then brought to life with contact with liquid water.
- Water bears (tardigrades) are complex multicellular animals (just 1.5 millimeters in length) that can survive in very harsh conditions. When they lose contact with liquid water, they go nearly completely dormant into a cryptobiosis state—a process that is not fully understood today. However, they can use a nonreducing sugar to protect their membranes from damage, even though they are almost completely dried out.
- In their cryptobiosis state, they can briefly survive extreme cold (-459°F , or -272°C), can briefly survive extreme heat (304°F , or 151°C), and can handle 1000 times lethal radiation. In fact, some species can live a decade without liquid water.
- In September of 2008, the TARDIS space program found that the animals did very well while exposed to both the vacuum of space plus solar radiation. These are the first animals to do this. No “normal” animals that we are used to could have survived these tests.
- Certainly, if full animals (water bears) can survive (for a short time) exposure to space in cryptobiosis, then the masses of more hardy

single-celled extremophiles—that scientists are now finding every day—should do even better. Indeed, some of the extremophiles seem happy to hibernate (cryptobiosis) for thousands to millions of years in rocks.

- It is not too much of a stretch to think of some hardy, simple prokaryotic cell hitching a ride on a piece of interstellar rock and falling onto Earth’s newly stable crust about 3.85 billion years ago. Indeed, it is curious that we have evidence of life all the way back to 3.85 billion years ago—right at the end of the heavy bombardment.
- It is surprising that while it took over a billion years to build slightly more the complex eukaryotic cell from the prokaryotic cell, it only took less than about 100 million years to start life, a process that we very poorly understand.
- Why do we have animal and microbial life on Earth that can survive in space? What about relic DNA? Maybe panspermia is an attractive way around these issues—certainly a quick way to start life on Earth.

Suggested Reading

Bennett and Shostak, *Life in the Universe*.

Irwin and Schulze-Makuch, *Cosmic Biology*.

Kaufman, *First Contact*.

Pyle, *Destination Mars*.

Questions to Consider

1. While the evidence for past Martian life in the Mars meteorite was initially compelling, most scientists today believe that it doesn’t provide unambiguous proof. What do you think?
2. Can panspermia lead to the whole galaxy being seeded with similar life?

Could Life Ever Have Existed on Venus?

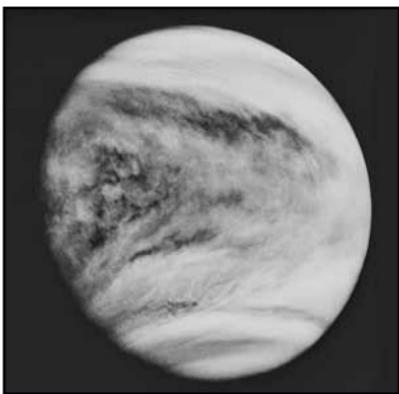
Lecture 12

Current life on the surface of Mars can be pretty firmly ruled out because liquid water is just not stable on the surface of such a cold, small planet. The next most logical place to look is Venus. After all, it is the closest planet to Earth, and it is almost the same size. In fact, unlike Mars, Venus has lots of atmosphere. In this lecture, you will learn that early Venus might have had liquid water oceans on its surface, but a runaway greenhouse has made today's Venus devoid of life and hellish.

Venus: Earth's Evil Twin

- Venus has none of the weaknesses that Mars has, but Venus has some serious problems of its own. It also serves as an excellent warning to the people of Earth of how things can go horribly wrong with an otherwise nice planet.
- Venus is about the same size and mass of Earth; it is only 5 percent smaller in diameter. It also has atmospheric compounds, such as CO₂ and N₂, like Earth. Its interior heat source is comparable to Earth.
- Venus is a similar distance from the Sun as Earth, but Venus is about 0.723 AU closer. Venus looks similar to Earth and should be just a bit warmer—about 30°C hotter.
- However, the Venusian atmosphere is almost 100 times thicker than Earth's and is composed of primarily CO₂, which creates the greenhouse effect. Venus doesn't have plate tectonics but, instead, suffers from occasional catastrophic volcanic resurfacing.
- Venus has a very hot surface temperature (750 K, or 891°F); for example, lead would melt at this temperature. In addition, liquid water is unstable on the Venusian surface.

- Venus rotates on its axis once every 243 days while Earth does this once every 24 hours. Venus's rotation is retrograde, meaning that it is in the opposite direction of its orbit. Venus is the only planet in the inner solar system to do this.
- A year on Venus is equal to 224 Earth days. Combine this with its own rotation to give a period of 117 Earth days between one sunrise and the next. Therefore, 1 day on Venus is equivalent to 117 Earth days.
- Although Venus is similar to Earth in many ways, its slightly closer proximity to the Sun (0.723 AU) creates a harsh atmosphere incapable of supporting life. The reason for this is Venus's atmosphere, which is hot and dry. This is the opposite of cold Mars.
- Venus has a remarkably thick layer of cloud cover—about 20 kilometers thick. The clouds consist of sulfuric acid droplets. The thick cloud cover will travel all the way around the planet in 4 days due to 200-mile-per-hour winds, which would have an amazing amount of force in the thick Venusian atmosphere.
- No visible sunlight reaches the surface of Venus. Thermal infrared heat energy is trapped on the surface because of the clouds, resulting in extreme temperatures.
- The CO₂ in the atmosphere contributes to the greenhouse effect on Venus, but it is joined by other gases—including SO₂, CO, and HCl—which help produce the extreme surface temperatures.



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In our solar system, Venus is the second planet from the Sun and is the sixth in size and mass.

- All of the water on Venus is contained in its atmosphere as water vapor (10 million atmospheres) because the surface is too hot. Contrastingly, if all of Earth's water were put into the atmosphere, there would be 100 atmospheres of atmospheric pressure. Today, Venus is extremely dry.

Life on Early Venus?

- Scientists estimate the amount of water initially present on Venus to be at least enough to create a global layer about 3 meters thick—about 0.15 percent of the Earth's water inventory—although it might have been much more. However, Venus has lost its water over time. The process by which this happened is called photodissociation.
- In photodissociation in Venus's atmosphere, an H_2O molecule (present in the atmosphere as water vapor) is broken down by sunlight. The hydrogen atoms escape to space, and the oxygen atom oxidizes surface minerals.
- On Earth, photodissociation is frustrated by the atmospheric structures. This does not occur on the Earth because the Earth is cooler (so water vapor stays lower in the atmosphere) and because the temperature increases sharply at 10 kilometers (the tropopause) and increases throughout the Stratosphere.
- Therefore, all the water vapor condenses at the lower (cooler) 10-to 35-kilometer altitudes, so very little water rises all the way to the ionosphere (greater than 50 kilometers above the ozone layer), where it would be photodissociated by the Sun's UV.
- If the Earth were picked up and placed at the same distance Venus is from the Sun, the atmosphere would begin to warm up because of the higher input of solar energy. The temperature would increase about 10 percent, or about 30 K.
- At 0.72 AU, Venus's solar constant is 192 percent that of the Earth's, so Venus has as much extra sunlight as Mars lacks. On Venus, much more water to vapor leads to a stronger greenhouse effect, which

causes oceans to evaporate and all carbon sinks die, resulting in a runaway CO₂ greenhouse effect. This causes the planet to lose water to photodissociation.

- The Earth is OK because of its location; it receives just 52 percent of the solar power that is received by Venus.
 - Lower terrestrial temperatures mean that Earth's atmosphere is capable of holding less water vapor.
 - Earth's atmosphere is stable at relatively low water abundances and temperatures.
 - Earth needs 40 percent more sunlight to trigger a runaway greenhouse effect.
 - Earth needs to be closer to the Sun or the Sun needs to put out more energy for a runaway greenhouse to develop.
 - The Sun's output does increase with time, so one day (in approximately 2 billion years), Earth will develop a runaway greenhouse naturally.
- Venus has no plate tectonics. The evidence for this is that no subduction and spreading zones have been picked up on radar, and therefore, no rock carbon cycle could have operated to try and keep the temperature down.
- There is so little water on Venus that even the mantle is dry. That makes viscous magma, which in turns makes regular volcanism difficult. Instead, there is evidence that approximately every 500 million years, there is a catastrophic resurfacing.
- Possibly 4 billion years ago, Venus might not have been so hellish. Its surface temperature might have been more conducive to life. The young Sun was much cooler than now, so Venus was, too. Perhaps life existed on Earth, Mars, and Venus simultaneously 4 billion years ago.

- However, over time, Venus heated up, developed a runaway greenhouse, and became too hot for life. Mars lost its thick atmosphere, cooled off, and became too cold for life. Earth remained just right for life based on liquid water (the Goldilocks planet).

The Habitable Zone for Complex Life

- Venus, Mars, and Earth are the three most promising planets in our solar system for surface life. However, having 192 percent of the Earth's solar power and a thick atmosphere (runaway greenhouse warming) has made Venus too hot for surface liquid water. Mars has just 44 percent of the Earth's solar power, a thin atmosphere (no greenhouse), and a cold core, leading to a cold, frozen world.
- Hence, it is clear that there is a special zone around any star where liquid surface water is possible. This zone is called the habitable zone.
- To have complex animal life on Earth requires a surface temperature in the range of 0°C to 100°C. It turns out that a patch of ground radiates power (P) as σT^4 back into space.
- Power incoming from the Sun equals power outgoing at the equilibrium planet temperature (T_{equ}), or to an order of magnitude $L_{\text{star}}/4\pi D^2 = \sigma T^4$. Correcting for the spherical shape of the Earth and the fact that radiation falls only on the dayside yields the following: T^2 varies as $\sqrt{L_{\text{star}}}/D$. For our Sun, $T_{\text{equ}} = 285/D^{1/2}$ Kelvin, r in AU. Because Earth is on average 285 K (11°C, or 53°F), $D = (285/T_{\text{equ}})^2$ AU.
- For $T_{\text{equ}} = 0^\circ\text{C}$ (273.15 K), $D = D_{\text{max}} = 1.1$ AU. At 0°C (32°F), this is the farthest an Earthlike planet could be from the Sun and have an average temperature to allow liquid water. (A larger greenhouse than Earth's could extend this to about 1.3 AU.)
- For $T_{\text{equ}} = 40^\circ\text{C}$, (313.15 K, the point at which a runaway greenhouse starts), $D_{\text{min}} = (285/313)^2 = 0.8$ AU. With an average

global temperature of about 40°C, this is the closest an Earthlike planet could be to the Sun and have liquid water.

- For L_{sun} and the Earth's level of greenhouse, we have a habitable zone from about 0.8 to 1.1 AU for surface liquid water. This zone excludes Venus (at 0.72 AU) and Mars (at 1.5 AU). Therefore, in our solar system, only the Earth can have liquid water on its surface.
- What about other solar systems? A more generalized form of the equation is as follows: $r_{\text{habitable}} = 0.8\sqrt{L_{\text{star}}}$ out to $1.1\sqrt{L_{\text{star}}}$, where L_{star} is the luminosity of the alien Sun in solar luminosities.
- Venus is just too close to the Sun to be in the habitable zone. It has suffered a runaway greenhouse and is hellish today. Perhaps 4 billion years ago, Venus was habitable, with warm liquid oceans. There is a small habitable zone, about 0.8 to 1.1 AU, where an Earthlike planet will have liquid water on its surface in our solar system.

Suggested Reading

Bennett and Shostak, *Life in the Universe*.

Jakosky, *The Search for Life on Other Planets*.

Questions to Consider

1. Do you think that Earth is becoming more like Venus?
2. Why is the habitable zone considered nonexistent for stars five times the Sun's mass or larger? (Hint: How long do these stars live?)

Liquid Assets—The Moons of Jupiter

Lecture 13

The moons of the giant gas planets may well harbor large reservoirs of liquids that could be home for exotic life. After looking for life in the inner solar system, the next target is the giant planet Jupiter, located at 5 AU from the Sun. In fact, Jupiter—the largest planet in our solar system—is not very habitable. Its lack of a stable surface makes it unlikely to have life. However, its four large moons are another story. In this lecture, you will learn about the history of how these moons were discovered and what potential life-bearing qualities they have.

The Discovery of the Icy Moons of Jupiter

- A little over 400 years ago, in 1609, Galileo was the first person to construct a proper 10x telescope (although he did not invent the telescope). He also was the first person to really study the night sky with a telescope in a scientific manner.
- What Galileo found was so impressive that the powerful Medici family, which controlled the city of Florence, asked Galileo to come to Florence and continue his work under their patronage. Galileo, who was definitely interested in their financial support, happily agreed.
- Galileo's discovery of the four main moons of Jupiter was a very important discovery at the time. It was certainly proof that some bodies orbited bodies other than the Earth.
- It was the first time a celestial clock had been found. After all, the times of the eclipses of moons of Jupiter, Galileo realized, were more accurate than hands of any clock. Galileo's Jovilab was a device that allowed the observer to note the position of each of the four moons and then know effectively what universal time it was.

- This was going to be Galileo's solution to the longitude problem for ships and make the Medicis even richer than they already were. It would allow ships to travel safely across the oceans—the biggest scientific problem of the day.
- However, it turned out that accurately determining which moon was which on ship at sea was too difficult with the simple telescopes of the time. The Jovilab was never really used widely, but it did work.
- In our solar system, there is simply no liquid surface water beyond the habitable zone (0.8 to 1.1 AU). While some estimate that this zone could go out to about 1.37 AU, it is clear that Mars is too far. Past the snow line (about 3 AU), the outer solar system has tons of surface H₂O; it is all just trapped in the form of solid ice—and where there is ice, there could be liquid water.
- However, the outer solar system is full of ice. In fact, water ice is thought to be very common on the moons of the gas giants. Therefore, while surface liquid water is out of the question, it is certainly true that subsurface liquid water is possible—if only we could find a heat source to melt the ice.

Jupiter's Moons

- The Jupiter system is composed of (from inner to outer major moons) Io, Europa, Ganymede, and Callisto. These moons are trapped in a mean motion resonance. In this 4:2:1 resonance, Io goes around Jupiter 4 times for every 2 times Europa does and every time Ganymede does.
- As a consequence of this dance, the moons pull on each other's orbits in such a way to increase the ellipticity of the orbits (ellipticity pumping in a mean motion resonance is common). Therefore, the ellipticity cannot be zero for any of the moons' orbits.
- When Io gets close to Jupiter, the $1/r^3$ nature of tidal forces raises 3000-foot tides on the surface of Io as it is stretched during its closest approach to Jupiter every 1.7 days. Hence, the friction of



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Jupiter has more than 60 known moons, including Europa and Io.

moving the rocks so much so often has released massive amounts of heat, which is literally melting Io.

- For the next moon out, Europa, the tidal heating is less severe; 15 percent of the outer icy shell of Europa is water. When the tidal heating is applied to Europa, it leads to an underground liquid water ocean (maybe just a few miles below the surface) that is maintained by the tidal heating.
- The NASA *Galileo* spacecraft mission was able to take excellent images of the surface of Europa. These images show cracks that are formed from these tides and solid ice (with a top layer that is brittle) on top of liquid subsurface water.
- The great thing about Europa is that there are rocks (maybe hot spots?) in contact with the ocean (we think). Scientists have an idea of what a cross section of Europa would look like today.

- Ganymede also likely has ice-water-ice layers, which may be a more common type of moon in our universe. A cross section of Ganymede suggests that it has liquid water in an ice sandwich—but it might also have a warm core.
- NASA and the European Space Agency (ESA) would like to send orbiters around both Europa and Ganymede to see just how these tides work and how thick the surface ice is. Also, they can use ice-penetrating radar to see under the ice and measure accurately the tidal displacements of the surfaces.
- The new orbiters from the proposed ESA/NASA Europa Jupiter System Mission include the Europa orbiter from NASA (which is now canceled) and the Ganymede orbiter from ESA called Laplace, which was renamed JUICE (JUPiter ICy moons Explorer).
- The Europa mission was selected as the first start, with a Titan mission to follow next. Now, there is just the European JUICE mission heading to Jupiter, launching 2023 and arriving around 2030. NASA is likely to build one camera for the JUICE mission.
- Of course, a key goal of the orbiter is to understand where to drill into the surface ice on either Europa or Ganymede and try to insert a robotic submarine into the ocean to swim around to find life. This scope is a bit too advanced for today's missions, but we can practice such missions on the dry valley lakes of Antarctica today.
- The ultimate mission is a Europa ocean explorer. The mission would drill through the ice and release a submarine that would search for life in the dark subsurface ocean.
- A mean motion resonance of the Galilean moons leads to tidal heating, which likely keeps a subsurface liquid water ocean a few miles under the surface ice of Europa and likely Ganymede as well. Therefore, subsurface life on the moons of giant planets may be possible—well outside the classical definition of the habitable zone.

- ESA/NASA will explore the rocky bottom of Europa's moon around 2030 and see if there really is a large liquid ocean in the JUICE mission to Jupiter's moons.
- Eventually, we may send in a submarine to see if life exists in that ocean, but that mission is still in the far future. However, JUICE will go a long way in telling us where to land.

Suggested Reading

Bennett and Shostak, *Life in the Universe*.

Questions to Consider

1. Do you think there is life in Europa's subsurface ocean?
2. What do you think a mission to tunnel through the thick, icy crust of Europa, in order to launch a minisubmarine, would yield?

Liquid on Titan and Enceladus

Lecture 14

Jupiter's icy moons can use tidal heating (from friction) to keep a liquid ocean of water from freezing below the solid ice surface of Europa. In this lecture, an extended tour of the outer solar system will lead you to a visit all the way out to 9.5 AU from the Sun to the giant planet Saturn. It is the moons of Saturn that interest astrobiologists because neither Jupiter nor Saturn has a solid surface for life. The moons of the giant gas planets may well harbor large reservoirs of liquids that could be home for exotic life.

Saturn's Moon Titan

- Saturn has an amazing array of moons. The largest moon in the solar system is Ganymede, which is just followed by Titan (including Titan's atmosphere causes it to be the largest) in the solar system. Titan is a moon that orbits around Saturn and has a massive 5150-kilometer diameter.
- Titan has long been an exciting place in the solar system because it is the only moon with a significant atmosphere. In fact, Titan has the thickest atmosphere in the solar system (except for Venus).
- Titan is at 9.5 AU from the Sun, so it gets just about 1 percent of the solar constant that the Earth gets. The temperature of Titan is -180°C . In the best of times, the Sun is weak, but Titan's surface is even darker due to its thick, ever-present cloud cover.
- Titan's atmosphere is predominantly N_2 but also contains small amounts of methane (CH_4). It has been theorized that Titan has global-scale oceans of methane, which continually resupply the Titan atmosphere with the small amounts of methane observed.
- Furthermore, it has been thought that the evaporation of methane in the atmosphere has condensed into clouds, creating Titan's thick cloud cover. However, observations tell us that Titan's atmosphere

is not saturated with methane, so the clouds cannot consist of methane.

- Another hypothesis given to explain Titan's thick clouds is that the global oceans that may be present consist of ethane and nitrogen as well as methane. This would fit well with the chemical compounds observed in the atmosphere, but observations contradict the presence of any such global oceans.
- Instead, it is more likely that the ethane-methane mixture does not reside at the surface in large open bodies of liquid; rather, it percolates up through the cracks and pores in the surface ice. It then evaporates into the atmosphere, helping to create the thick cloud cover.
- The best way to resolve a mystery like this is to simply visit the world. A combined NASA/ESA mission to visit Saturn carried along a lander (called the *Huygens* lander), whose role in the mission was to detach from the *Cassini* spacecraft and land on the surface of Titan. This was a real chance to land on a very strange, foreign world, a world much different from Mars—an icy, frozen world on the outskirts of our solar system.
- To survive the landing, the spacecraft had a parachute that would deploy at just the right moment and bring the lander down nice and softly. This was the first mission that was designed in which we had no idea what the lander would land in. It was not obvious whether it was going to land on solid ground or in the middle of a large lake or ocean of liquid methane.



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Saturn is the second largest planet in the solar system and is the sixth in distance from the Sun.

- It was a great deal of worry that perhaps the lander would sink, disappearing underneath a lake of liquid methane, which would be a disaster. Therefore, the lander was designed to have the ability to float on whatever it landed on, so that was quite an exciting solution to a difficult design problem. It took the world's best engineers to come up with a system that would safely get the lander onto the surface of Titan.
- The radar on the NASA *Cassini* probe was able to find very dark (absorbing) patches on the northern regions of Titan. These are now thought to be true lakes of liquid methane. Outside of the Earth, these are the only surface liquids known in the solar system. Because the surface temperature of Titan is 94 K (-179°C), any liquid is likely methane; all water is frozen solid everywhere on Titan.
- An atmospheric haze of organic molecules is formed by chemical reactions involving methane and ethane and driven by the Sun. The organic molecules that saturate the atmosphere condense out and settle into the methane-ethane oceans/lakes. Sediment of these organic molecules is formed. Heat (from occasional impact events) will form ponds consisting of a slurry of water, methane, ammonia, and organic compounds. This slurry is very similar to what might have been present on prebiotic Earth.
- However, any liquid water that would be produced by an impact would freeze too quickly, and if it freezes hard and solid, one can't really expect much biological activity to occur. Therefore, there really needs to be life with liquid methane as its solvent to thrive on Titan.
- On the southern tip of Titan is a very large lake called Ontario Lacus because it is quite close to the size of the Great Lakes that are located in North America. Specifically, it is quite similar to the size of Lake Michigan. The lake has a shoreline, and mountains rise up in the background. Around the lake are some rivers and river deltas.

- There is pretty compelling evidence that the lakes on Titan are not terribly different from the lakes on Earth. It is amazing that such Earthlike structures are able to exist at temperatures of just 94 degrees above absolute zero. This is an ice world that is cryogenic, colder than we can possibly imagine, yet we see structures that look remarkably similar to our home. Perhaps there really is life out there.
- As final proof of the existence of the northern lakes of Titan, we can see glints of sunlight shining off of them. You cannot get a glint of sunlight any other way than having a liquid body between the planet and the Sun.

Saturn's Moon Enceladus

- A major discovery of NASA's *Cassini* spacecraft was fine particles of water ice and water vapor erupting up from Enceladus. This was a huge surprise for planetary scientists to see such activity so far out in the solar system.
- Scientists have an idea of what causes these geysers. Tidal forces acting on fault lines in the moon's icy shell cause the sides of the faults to rub back and forth against each other, producing enough heat to transform some of the ice into plumes of water vapor and ice crystals, according to a study published in the journal *Nature*.
- The *Cassini* spacecraft passed close to Enceladus and quickly passed through the plume. It sampled that plume and found evidence for salt in the dust particles, which tells us that there must be liquid water in contact with rock to get that salt dissolved and ejected.
- There are deep surface cracks that are the source of the geysers. Tidal forces allow the rubbing and heating to power the geysers.
- On Titan, it is very cold (-179°C), but methane is liquid under its thick atmosphere. There are lakes of liquid methane, which might

host life—if it can use methane as a solvent. A future NASA mission to these Titan lakes is in the planning phase.

- Tidal heating likely keeps a subsurface liquid water ocean within a few miles under the surface ice of Enceladus, so even as far out as Saturn (at 9.5 AU from the Sun), there can be subsurface liquid water.

Suggested Reading

Bennett and Shostak, *Life in the Universe*.

Questions to Consider

1. Do you think the Titan *Huygens* probe will be the last time in our lifetimes that we will land on an icy moon?
2. Do you think that there could be life in the cold liquid methane lakes of Titan? What could this life be like?

Discovery of Extrasolar Planets

Lecture 15

In this lecture, you will learn that astronomers detect planets in three ways: by measuring the small radial velocity wobbles that the planet exerts on its parent star, by the small amount of light it blocks as it transits across the face of the star, or by directly imaging the small amount of light they emit if they are young and still hot. Of the over 800 such planetary systems detected, less than 1 percent are similar to Jupiter. Most are much closer and orbit on much more eccentric egg-shaped orbits. This means that solar systems as we know them are unlikely in more than 99 percent of the alien solar systems found so far.

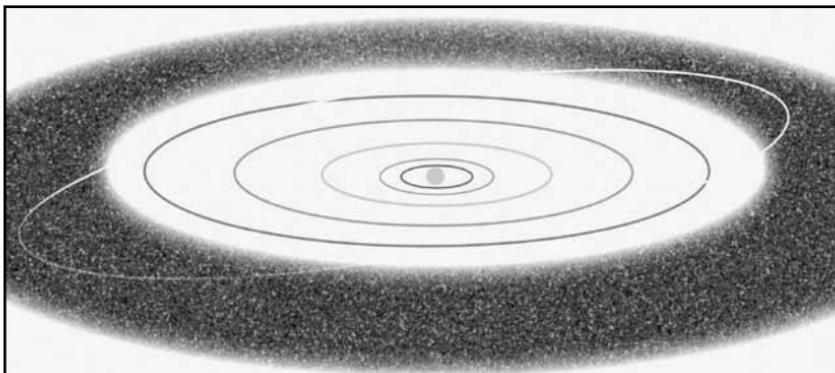
What Are Planets?

- Astronomers have now detected hundreds of new planets around other stars; it appears that nature typically creates solar systems that look very different from our own.
- Are there other places in the universe like Earth? You might think so, but it's been less than two decades that astronomers started detecting any planets around other Sunlike stars.
- Throughout the filming of the *Star Trek* series, for example, we had no idea if there was even a single planet outside our solar system. Extrasolar planetary science is really a new field of science with many unsolved mysteries.
- Planets around other stars are important because life needs a stable platform like a planetary surface (and maybe liquid water) to thrive. In order to find life elsewhere in the universe, it is first necessary to understand what sort of planets are common in the universe and what sort of solar systems are common.

- There is a lot of debate on the topic of what makes a planet a planet, but astronomers generally agree that the following ideas are true for all planets.
 - It must be clearly in orbit around a star.
 - It must have formed from the gas and dust around the star as it was forming from a disk around a star.
 - It must have a mass that is less than 13 Jupiters (no nuclear fusion on a planet) and be massive enough to be close, spherical, and ball-like in shape.
 - It must be the dominant mass in its part of the solar system.
- Pluto fails to meet the last criterion because it is just a large individual member of the much larger Kuiper belt, an asteroid belt at the edge of our solar system of which Eris is the largest member. Pluto is now called a dwarf planet by astronomers, like Ceres in the asteroid belt.

The Search for Extrasolar Planets

- Giordano Bruno was a Dominican friar and astronomer. He is often credited with being the first to posit that there might be an infinite



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The Kuiper belt consists of hundreds of millions of objects that are supposedly leftovers from the formation of the outer planets.

number of other worlds among the stars—that each star in the night sky could itself have a solar system similar to our own.

- The idea that there would also be an infinite number of civilizations—and Gods—got Bruno into trouble with the church, and he was burned at the stake in 1600 by the Roman inquisition. The field of extrasolar planetary studies was off to a rough start.
- Luckily, astronomers are now at peace with the church, and in fact, the Vatican runs the Steward Observatory at the University of Arizona, where the fathers are expert astronomers.
- Bruno’s idea could not be scientifically checked until 395 years had passed. Science could split the atom, land people on the Moon, and send spacecraft across our own solar system—but couldn’t detect a single planet around another star.
- The technique that has discovered the most planets is the radial velocity method. This technique is simple in principle: To find a planet, astronomers look for a “wobble” as the mass of the planet pulls the star around the center of mass of the system.
- However, this “wobble” is so small that we cannot just look to see if the position of one star is slightly changing on the sky. Instead, astronomers have developed a very sensitive way to observe slight changes in the velocity of the star.
- The idea has two parts: Light is a wave (red light has a longer wavelength than blue light), and the Doppler shift forces the pitch of the light toward blue wavelengths as an object moves toward you.
- A star with a planet gets slightly bluer as it moves toward the Earth and slightly redder as it moves away. The bigger the planet, the bigger the shift, and the closer the planet, the quicker “1 year” takes and, therefore, the quicker the planet can be discovered.

- Radial velocities have allowed us to discover new worlds, but to find Earth-mass planets at 1 AU around Sunlike stars, we need another approach. A really simple way to detect planets is to notice the slight dimming of the host star if the disk of the planet passes (or transits) across the face of the star.
- Scientists have even discovered another planet in orbit around a star by seeing slight changes in the inner planet's transits as another new outer planet affects it. With both techniques, we have now found well over 800 alien planets.

New Solar Systems

- At 5 AU, all known planets are Jupiter-like in mass, which is a selection effect of the techniques. However, if we look at the eccentricity—or the “ovalness” of all the best characterized alien planets discovered to date—a disturbing trend emerges.
- These giant outer gas planets do not have circular orbits like Jupiter. In fact, only a few (about 4/450, or less than 1 percent of extrasolar systems) have outer giants in circular orbits.
- How can we really know that these are Earthlike planets that can support life? While radial velocity and transit methods are very good at finding planets with short orbits, they both fail to find planets with orbits much past about 6 AU—because it takes most of a decade of sensitive measurements to detect such planets.
- Direct imaging is advantageous because it does not require the planet to orbit around the star; we just need to see that it is moving with the star through space.
- Direct imaging tells us that there is thick methane gas on planet SCR 1845B (just 10 light-years from Earth). The triple solar system of giant planets called HR 8799 consists of a 7-Jupiter-mass planet 69 AU from the star and three 10-Jupiter-mass planets at 18, 24, and 38 AU from the star.

- If we look at all the imaged planets, we see selection effects at play. Most directly imaged planets have masses near that of brown dwarfs. They are also all self-luminous and, therefore, much younger than the radial velocity or transit objects.
- One of the puzzling results of these discoveries lies with the Jupiter-sized planets because their orbits are close to their central star, a location we expect to find more rocky planets like in our own solar system. We believe these “close Jupiters” must have formed at 5 AU like our Jupiter, but these other Jupiters migrated toward their primary star.
- It is now pretty clear that most planets form by a process known as core accretion. Now, we know that stars with more heavy elements have more planets, and larger planets are observed. This is a key prediction of the core accretion process. This may not be true of low-mass planets, however.
- Most astronomers think that gas giants are formed in the outer solar system, where 10 to 30 Earth-mass cores are quickly made (in about 1 to 5 million years). Then, the hydrogen and helium gases can be gravitationally accreted.

Suggested Reading

Seager, ed., *Exoplanets*.

Questions to Consider

1. Why are the largest planets (and those that are closest to their star) easiest to find? How is direct imaging of young planets different? Can they be found at wider separations?
2. Do you find it surprising that more than 99 percent of the alien gas giants do not resemble our own gas giant Jupiter in terms of these alien Jupiters being mainly on noncircular (or much smaller) orbits?

The *Kepler* Spacecraft's Planets

Lecture 16

Kepler is the first space mission designed to determine how common Earthlike planets are around Sunlike stars. In this lecture, you will discover that Earthlike worlds in the habitable zone could be fairly common around Sunlike stars. The very early results of *Kepler* show that if you are given 100 Sunlike stars, for example, it is probable (although optimistic) that there should be about 34 Earthlike planets—planets that are close to the Earth in mass and close to the habitable zone.

NASA's *Kepler* Mission

- To be able to understand how common (or rare) life in our universe is, we need to understand how many rocky planets exist in the habitable zones of other stars.
- Small rocky planets like Earth are just $1/320^{\text{th}}$ the mass of Jupiter and, therefore, are nearly impossible to detect with radial velocity or direct imaging.
- However, we can detect small planets if we are lucky and they pass right in front of the star each orbit. In other words, every one out of 1000 or so planets will cross right in front of its star, making it get dimmer.
- The amount of dimming is trivially the ratio of the areas: $\text{dim} = \text{area planet}/\text{area star}$.

$$\begin{aligned}\text{dim percent} &= 1 - (R_{\text{planet}}/R_{\text{star}}) \\ &= \text{about 1 percent for a Jupiter} \\ &= \text{about 0.01 percent for an Earth}\end{aligned}$$

- It is pretty easy to do 1 percent photometry from the ground (even with small 10-centimeter telescopes). However, the mixing of the air makes it impossible to do 0.01 percent from the ground. Therefore, while we can find transiting hot Jupiters from the ground, we cannot detect much smaller (10 times smaller) rocky Earthlike planets. We need to go into space to do that.
- The *Kepler* mission is actually very simple. It looks into a dense region of stars about 500 to 3000 light-years from Earth. The mission is simply to stare at 157,000 stars and take images every 30 minutes for the life of the mission. Because *Kepler* is in space, it can look at these stars continuously, so any transits will not be missed.
- The optics of *Kepler* are very special to capture a 115-square-degree field (two scoops of the big dipper). The place in space is near Cygnus. It has over 157,000 stars that are the right brightness to search for planets.
- The charge-coupled device (CCD) is a massive 95-million-pixel array. Only the CCD pixels that have a predetermined target star are read out. Also, the pixels are very large (4" on the sky), and the telescope is slightly out of focus—pall to give better stability in the photometry.
- *Kepler* was launched from Cape Canaveral on March 7, 2009, and it has been extended to work through 2016. How well does *Kepler* work? The answer is very well. It is so sensitive that it can actually see details that have never been seen in optical transit data before.
- The *Kepler* mission is still running, so it is difficult to have definitive numbers as results. Only candidates for planets are known now (about 2000 of them today), and many of these (70 to 90 percent) will be, in fact, true planets. We already have complete sampling of all planets in the field with short orbital periods (less than 42 days) with great certainty.

How Common Are Earthlike Planets?

- We don't really know how many Earthlike planets there are quite yet, but *Kepler* does tell us a few things right now. By looking at the *Kepler* data, we can make some guesses about how common Earthlike planets are.
- Dr. Wesley Traub of JPL/NASA tried to come up with a good extrapolation of the *Kepler* data. In other words, we can take the data and project it farther away from the stars than it has been completely measured to date and, in this extrapolation, understand how common Earthlike planets are around Sunlike stars.
- Hot Jupiters, which are Jupiters that have periods of only a few weeks to a few days, are quite rare in the *Kepler* data set. *Kepler* finds very, very few of these. Before *Kepler*, we knew about a lot of them, but that was because they were really the only things we could detect, and we have an unbiased way of looking for these objects with the *Kepler* spacecraft.
- If you have a transiting planet that has been detected, you have a very lucky alignment; that planet is just aligned across the disc of a star. The probability of that happening turns out to be a very simple ratio of the radius of the star divided by the distance between the star and a planet, which is D .
- The bigger the star, the bigger the radius is, the



Kepler-20f is an Earthlike exoplanet that was recently discovered by NASA.

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more likely you will see it, and the smaller the distance is of the planet away from the star, the more likely you will see it.

- As an example, for a hot Jupiter that maybe has a period of about 5 days going around a Sunlike star, there is actually a 10 percent chance, given a full set of random orbits, that you will be able to see a transit occur because it is a very close planet around a relatively large star, like our Sun. That can define a probability that you have a transit.
- Of course, the inverse of that probability is the probability of not having a transit. Therefore, there is a pretty large correction factor. In other words, we are just sampling the tip of the iceberg with the transiting planets. We know that there are many, many more planets that do not transit, so we have to make a correction for that effect. This is very important with the *Kepler* data.
- Luckily, it is not terribly complicated to make this correction. Most of the *Kepler* stars have been selected to be Sunlike stars, so those 157,000 stars are handpicked to have masses that are similar to that of the Sun. There are a few low-mass stars included as well, but for the most part, the objects are right around the mass of the Sun, and those are the ones we are considering in this effort.
- If we only look at the candidates that have been detected by *Kepler* that are periods between 4 and 6 days, we know that there should be a 10 percent chance that we are detecting these objects as transits. That means that we are missing 90 percent of the planets in that 4-to-6-day period.
- If *Kepler* looked at 1000 stars and of those 1000 stars, 20 had planets with periods from 4-to-6-day periods, that is a 2 percent success rate. If we know that we are only detecting 10 percent of the population, that tells us that the population of planets around those Sunlike stars should be increased by a factor of 10, so 20 percent.

- We simply multiply the detected rate, 2 percent, by a factor of 10 to come up with our true parent population—the true population of planets that we are trying to tease out—which is 20 percent.
- Now that we understand how to correct the *Kepler* observations, we can simply look at how many planets *Kepler* was able to discover as a function of the different periods the planets had, and we can build up a power law—a distribution of how nature populates alien solar systems with planets. In a sense, we are guessing at what the *Kepler* mission will find after the final analyses of its data.

Extrapolating *Kepler* Data

- *Kepler* is the premier planet-finding telescope today. We know now that Neptunes are more common than Jupiters.
- If we extrapolate the results of *Kepler*, it looks like approximately 29 percent of Sunlike stars have extrasolar planets with periods that are less than 42 days, so it is likely that almost every star has one or two planets if all periods are allowed—but this is just a guess.
- If we extrapolate further and look at periods that *Kepler* has not fully explored yet (through the habitable zone), we find (as Traub did) that the number of planets seems to be increasing with semimajor axis (close to linearly) until about 20 AU, where there is a steep cutoff down to a weak tail.
- The frequency of Earthlike planets in the habitable zone could be as high as about 20 to 48 percent around single Sunlike stars. This is just an educated guess, but it is our first real data on this tricky problem for humankind. However, it is important to note that only about 10 percent of the Milky Way stars are single Sunlike stars.

Suggested Reading

Seager, ed., *Exoplanets*.

Questions to Consider

1. Why is NASA's *Kepler* mission so different from, for example, that of the Hubble Space Telescope?
2. Extrapolating from the *Kepler* results, what is the chance that there is a habitable Earth around a Sunlike star?

A Tour of Exotic Alien Solar Systems

Lecture 17

Many of the solar systems that have been detected appear to have inner planets on noncircular orbits—but only a few might have habitable planets. So far, none look promising for life. In this lecture, you are going to be introduced to an overview of the four main classes of objects, ranked by mass or size. You are also going to be exposed to highlights of some of the most interesting examples of each of these new classes of alien worlds.

Different Types of Planets

- From *Kepler*, there are generally thought to be four groups of transiting planets (from most to least massive).
 - Hot Jupiters (mostly known about pre-*Kepler*): Less than 3 percent of Sunlike stars have these less than 42-day periods.
 - Hot Neptunes (mostly detected by *Kepler*): About 20 percent of stars have these less than 42-day periods.
 - Super-Earths (mostly detected by *Kepler*): About 9 percent of stars have these less than 42-day periods.
 - Earths (just now being found by *Kepler*): We don't know yet how common these really are.
- Hot Jupiters are the end product of migration in a solar system. They are very different from our Jupiter. They typically are less than 0.2 AU from their star and have orbital periods of a week or less (compared to 11.9 years for Jupiter).
- Hot Jupiters are very hot—about 1700 K (2600°F) compared to 165 K (−160°F) at 1 barometer for Jupiter. Because of this short period and their large size, hot Jupiters are the easiest to find with the radial velocity or transit methods. However, *Kepler* tells us that

they are actually quite rare; about 3 percent of Sunlike stars have such objects as planets.

- Before *Kepler*, we were finding a few lower-mass transiting planets. Some of the first of these were called exo-Neptunes or super-Neptunes (with masses around 20 to 30 Earths).
- In fact, a team of undergraduates at the University of Arizona was able to use a small 1.5-m telescope (the Kuiper) on Mt. Bigelow to confirm the planet HAT-P-11b.
- After one night of observing in good conditions, the team was able to compare it to the discovery transit and determine that the period is equivalent to 4.8878045 ± 0.0000043 days. That is, the team determined the length of a year of an exo-Neptune to within 0.4 seconds.
- In addition, the team was able to determine the radius to 0.45 ± 0.02 Jupiters (1.3 that of Neptune), making it one of the closest planets to the Sun known. However, its mass (measured by radial velocity) is quite large at 25 Earths (Neptune is 17).
- For transiting planets, we have radii (r) and masses. Hence, bulk densities are trivial to calculate: Density = mass/($4/3\pi r^3$). We can compare the radii and the mass of the known transiting planets (with good masses, which rules out most of the *Kepler* field).
- Sometimes, *Kepler* can use the changes in the timing of the transits in multiplanet systems (as each planet slightly pulls on the other) to have accurate measurements of the masses of the planets in that system.
- A spectacular example of this is the Kepler-11 system with six planets—all transiting. Therefore, very flat planar systems (like our own) do exist.

Super-Earths and Earthlike Planets

- There is a wide range of planet masses. In particular, we are starting to detect a lot of objects in the super-Earth range. These are planets that are between Neptune (17 Earths) and the Earth in size. They typically have lower density than the Earth. They may have thick atmospheres of hydrogen and helium like Neptune, but they may also have a rocky core. Some might even be close to 100 percent water.
- Kepler-11 is a six-planet solar system, and at least four of the planets are super-Earths. They likely have rocky cores with thick atmospheres of hydrogen and helium gas. We need better masses to have better estimates; these will come with time.
- Probably the nearest and most famous super-Earth is GJ 1214b. It is 2.7 times the Earth's size and 6.5 times its mass. It was detected by a small telescope in Arizona as it passed in front of its small (just 15 percent the mass of the Sun) star every 1.5 days. It is important because at just 13 parsec (42 light-years), it is close enough for detailed study.
- We are now just beginning to probe for truly Earth-mass planets. It is important to note that one pulsar planet is less than 1 Earth mass. The best examples of these objects are from the *Kepler* mission, which found (using the transit timing variation technique) two planets in a system—the Kepler-20 system, which is made up of five planets—that are Earthlike in mass and size (but are much hotter).



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Although scientists do not yet know how common Earthlike planets are, they do know that planets exist that are rocky and terrestrial like Earth.

- While we can now detect Earth-mass planets, we really want to know which of these are in the habitable zone. The problem is that the usual selection effects mean that the inner, small planets are found first, and these are too hot. In fact, neither Kepler-20e nor Kepler-20f have any chance of water; they are very hot rocks at 1400°F, which melts glass, and 800°F, which is hotter than Mercury, respectively. These planets are completely dry—and likely dead.
- There has been a recent discovery of a super-Earth in the habitable zone of Kepler-22b's star. Kepler-22b is 0.85 AU from its Sunlike star. It would be a cool 22°F (-11°C), a bit like Canada, ignoring all greenhouse effects. Earth would be -0.4°F without our greenhouse. If we add a bit of an Earthlike greenhouse, this turns to a lovely 71.6°F (22°C) on Kepler-22b.
- However, the problem is that it is 2.4 times the size of Earth, so is likely about 10 to 20 Earth masses (although we don't know for sure yet). Therefore, it might have a more Venus-like greenhouse (860°F, or 460°C) than an Earthlike greenhouse.
- Kepler-22b is also likely to have a thick hydrogen and helium atmosphere and to look more like Neptune than Earth. However, its moons (if it has any) could be fine for liquid water if they are massive.
- Another habitable zone system is the four-planet GJ 581 system. No system has probably generated as much excitement (and press releases) as the multiplanet radial velocity system GJ 581. It is just 20 light-years from Earth.
- It is thought now that maybe GJ 581d is in the habitable zone (due to a strong greenhouse), but like Kepler-22b, it is more than 6 Earth masses, so it is more likely a super-Earth or super-Neptune, which means that there is no liquid water.
- There was a claim that GJ 581g is a super-Earth right in the habitable zone, but that claim seems to be fading as more data is analyzed. In complex multiplanet systems, the interpretation of the

radial velocity data can be complex, so different groups sometimes find different numbers and locations of planets. In addition, GJ 581c was once thought to be in the habitable zone, but it looks to be too hot to have liquid water.

- Could GJ 581d have liquid surface water? It only gets 30 percent of the light that Earth does, so it likely has ice. However, it could have a very strong greenhouse. It could have a deep liquid ocean, but it is unlikely.
- Scientists have discovered four informal classes of planets. Currently, Neptunes seem to be the most common mass planets. However, astronomers have detected quite a few super-Earths as well. There are a handful of Earth-mass planets (including Kepler-22e and Kepler-22f), but none, so far, are in the habitable zone. There are also a few low-mass planets in the habitable zone (including Kepler-22b and GJ 581d), but these tend to be super-Earths and are likely closer to Neptunes than Earths.
- The good news is that we are just starting to look, and *Kepler* is still working on its data. It was not expected that *Kepler* would have found Earthlike planets in one-year orbits with enough certainty at this time—so we wait. However, it is clear that super-Earths (and true rocky planets) are common.

Suggested Reading

Seager, ed., *Exoplanets*.

Questions to Consider

1. What are the four main classes of exoplanets discovered by *Kepler*?
2. Astronomers can calculate the bulk density of rocky transiting exoplanets, but can they determine if there are thin atmospheres around these rocky planets? Why or why not?

Extraterrestrial Intelligent Life

Lecture 18

This lecture attempts to answer the following questions: How common is simple life in our universe? Even if simple life might be common, how likely is complex intelligent life to arise? There is excellent evidence that simple microbial life might be very common in our universe. Alien intelligent life will be much more rare than simple life, but no one knows for sure what this ratio is. Alien life will have some things in common with us, but in general, they will likely appear and act very differently than we do.

From Simple to Intelligent Life

- Extremophilic microbial life is much hardier than expected on Earth. In hibernation, even quite complex animals like water bears can survive UV radiation and the dry vacuum of space. We can only guess that there are microbes of Earth with even more impressive abilities. This makes a case for panspermia—especially considering how fast simple life appeared on Earth in just 100 million years or so after the crust was stable.
- In addition, the *Kepler* mission showed us that there are possibly as many as one Earthlike planet for every three Sunlike stars (optimistically, but no less than three planets per 100 stars) from extrapolating the *Kepler* mission data. We know that there are about 74 such stars within 32 light-years. That means that within 32 light-years of Earth, there could be $74/3$, or about 24 Earthlike planets.
- In the future, if we remotely detect microbial life on any of these nearby Earths (or if we find it on Mars, Europa, or Titan), then we know that the universe is teeming with simple life.
- The odds are pretty good that we will find exolife, but it will likely be quite simple in nature. This is an exciting quest for science and

will be a hallmark occasion for humanity. One hopes that these questions will be answered in the next decade or two.

- Even though simple life might be widespread in our universe, how common is intelligent life? After all, human beings are intelligent life, but are we alone—or not? To answer this, we can at least use the Earth as a template for the process of how life evolved into intelligent life.
- It is not at all clear that intelligence was a direct outcome of evolution: There is much debate on this topic, but it is clear that at some level, intelligence and technology does allow one to survive better, and hence, natural selection will favor intelligence.
- Roughly, evolution proceeded as follows: common ancestor to prokaryotes to eukaryotes to Cambrian explosion to dinosaurs to mammals to humanity. The approximately 200,000 years that modern humans have been on Earth is just 0.004 percent of the Earth's history.
- We need not consider in too much detail the individual steps, but the overall timeline is interesting with respect to the lifetime of the Sun. The Sun is fusing heavier and heavier atomic nuclei in its core (more helium and less hydrogen); it is getting denser and hotter because the rate of fusion depends sensitively on temperature in the core—it's getting brighter. Hence, the habitable zone is moving farther from the Sun with time, so in about 1 to 2 billion years, the Earth will be too close to the hotter Sun for life.
- While it took just about 100 to 200 million years for life to start on the Earth (from the time that the crust was first stable), it is sobering to note that intelligent life on Earth took another 3.5 to 3.7 billion years (about 30 times longer) to develop. It is even more sobering to realize that our Sun is growing denser and hotter in its core and, hence, is growing hotter and larger with time.

- In just about 600 to 1000 million years, the Earth will not be in the solar system's habitable zone. If we are still around, we can move on, but if intelligent life had required 4.7 billion years (just 20 percent longer), then the odds of intelligent life on the Earth would be zero.
- It was certainly good that life got off to a quick start (panspermia?) and that none of the other steps took longer than they did. This suggests that although simple life might need only about a 100-million-year stability window (or less) to arise on a planet, it needs about 4 billion years of stability for intelligent life to arise.

Rare Earth

- How many planets can be in the habitable zones of their stars continuously for more than 4 billion years? The answer is that we don't know. It worked on Earth, but the Earth might be a bit more rare than you'd expect.
- There is a famous theory called rare Earth by Peter Ward and Donald Brownlee that states that although microbial life might be common in the universe, intelligent life is not nearly as common. In fact, the Earth might be the only planet with intelligent life in the galaxy. Ward and Brownlee make a series of arguments that the Earth has been specially blessed compared to other planets.
- The Sun is in the right part of the galaxy—it is not too close to the crowded center, and it is not on the element-poor edges. However, 50 percent of stars in the Milky Way are like this.
- The Sun is the right kind of star; it is not too big or hot and not too small or cold. Only about 10 percent of Milky Way stars have masses in the range of 0.7 to 1.3 solar masses (only 5 percent have 0.9 to 1.1 solar masses). However, that is still more than 5 billion stars in the Milky Way alone. In fact, Sunlike stars are somewhat rare.

- The Earth has a hot core, plate tectonics, and a carbon-rock cycle to stabilize its temperature, but this might be common for Earth-mass rocky planets in the habitable zone.
- The Earth has a rare large moon to stabilize its spin axis and make tide pools. Large moons might be rare, but even without the Moon, the changes in the tilt of the spinning Earth is still slow, and the Sun can also make tide pools—just not as well as the Moon can.
- The Earth has the right amount of land and ocean for animal life, but maybe about 50 percent of Earthlike planets would, too. There must be a range that works fine.
- The Earth is lucky to have Jupiter on a circular orbit to protect it from comets and asteroids, but we know that at least about 1 percent of exoplanetary systems also have that. Furthermore, maybe it is not strictly needed.
- If we simply multiply all of these factors together, we will find that, indeed, photocopies of our Earth and solar system are very rare. For example, astronomers think that the type of massive collisions



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The Earth's moon has inspired much curiosity and intrigue throughout history.

that formed the Moon might be very rare, with a guess that one in 10,000 Earthlike planets could have moons.

- We know that less than 1 percent of other solar systems have Jupiter-mass planets on circular orbits past the snow line. These two facts alone (moons and Jupiters) mean that only one in one million Earthlike planets would actually have a large moon and a protective Jupiter.
- If only 5 percent of stars are Sunlike, and of those, only 3 to 30 percent have Earths, then if we have 100 billion stars in our galaxy, then that leaves us with $10^{11} \times 0.05 \times 0.3 = 0.15$ to 1.5 billion “kind-of-Earthlike” planets in the Milky Way right now.
- However, only one in one million would have a Jupiter and moon, which leaves just 150 to 1500 Earths. If we add to that the need to be in the right part of the galaxy (only 50 percent), have the right amount of land and water (only about 20 percent), and have plate tectonics and a carbon cycle (only about 20 percent), then we have only $0.5 \times 0.2 \times 0.2 = 0.02$ —just 2 percent work out.
- According to rare Earth, that means that we’d only have about 3 to 30 truly Earth photocopy planets in our galaxy right now, and they would all be very far (more than 1000 light-years) from the Sun.
- However, perhaps not all of these points are critical for intelligent life. Truly, no one knows for sure. Moons and Jupiters may very well not matter at all to some kinds of alien life, which would make our estimate low by a factor of a million times. However, it is clear that intelligent life is much more rare than simple life in our universe.

What Would Aliens Look Like?

- Intelligent life that evolved on another world would look and be very different from us. There might be some things in common, such as the notions that carbon chemistry seems very likely to be critical, liquid water seems like a good solvent, and other life-forms

are likely complex and multicellular. However, these very generic points are probably all that we would have in common.

- In the movies, for example, the aliens are usually incredibly similar to us. They have two arms, two legs, and a face. They speak (often English) and see and read as we do. In reality, they would be unlikely to have faces or stand upright.
- There is a real lack of imagination of how wonderful life in our universe really must be. Even the better special-effects aliens are pretty anthropomorphic. There is a real lack of imagination in Hollywood—and maybe in all of us—about how aliens might look and act.

Suggested Reading

Ward and Brownlee, *Rare Earth*.

Questions to Consider

1. Why do scientists think that simple microbial life might be very common in the galaxy (maybe even in our own solar system)?
2. How long did it take for intelligence to evolve on Earth? How much longer is this than the approximately 10 to 100 million years it took for simple life to start after the late heavy bombardment ended?

SETI—The Search for Intelligent Life

Lecture 19

Perhaps the Earth is in a galaxy full of simple life, but intelligent life is rare. However, evolution is certainly universal and might push all life to intelligent life. Searching for extraterrestrial intelligence (SETI) is the only way to address these issues. The search is small, but it is getting more sophisticated. In this lecture, you will learn that SETI is uniquely high-risk and high-reward research. The answers are out there—we just have to be clever and patient.

The Drake Equation

- It is hard to imagine that among about 100 billion stars in the Milky Way that we are alone—especially if you consider that there are about 100 billion galaxies in our universe.
- While the prevalence of extraterrestrial intelligent life is unclear, there are some scientists that feel that intelligence is a likely end product of evolution while others fear that such large brains (requiring a large number of calories to sustain) is an unlikely path for evolution.
- It is clear that this discussion, while entertaining, cannot answer these questions with any clarity without actually going out and actively looking for intelligent life among the stars.
- We need a metric to gauge the likelihood that there are intelligent communicating civilizations out there before we engage in a full-blown search for extraterrestrial intelligence.
- The Drake equation is a simple multiplication of probabilities to yield the number of intelligent communicating civilizations, on average, in our galaxy: $N = R^* \times f_s \times f_p \times n_e \times f_l \times f_i \times f_c \times L$

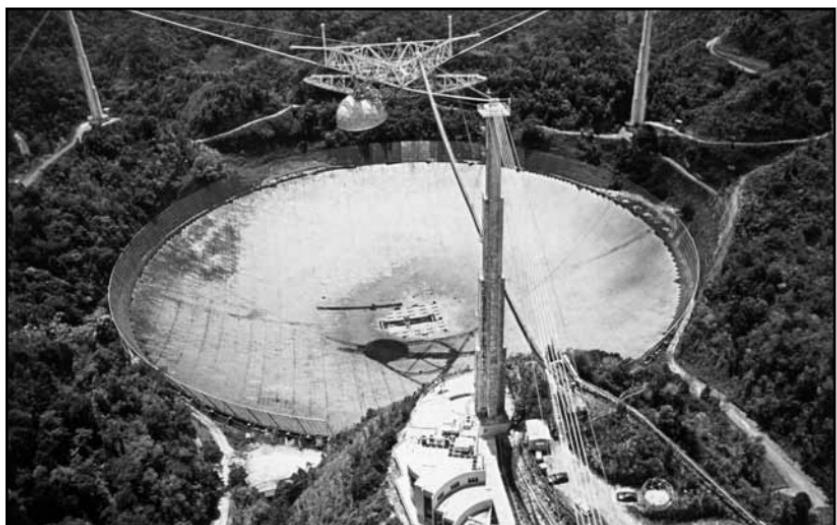
- The first term (R^*) is the number of new stars made each year in the galaxy (in stars per year). The fraction of stars that have the possibility of planets is f_s . The fraction of those that actually have planets is f_p . The number of Earths in each of those systems is n_e . Those Earths that have life is f_l . The fraction that have intelligent life is f_i . The fraction that are actually communicating is f_c . The last term, L , is the most important; it is the lifetime (in years) that the extraterrestrials will be transmitting those signals.
- If you were an optimist, you could say that $N = 6 \times 0.5 \times 0.5 \times 1 \times 0.5 \times 0.5 \times 0.5 \times L = 0.2L$. Therefore, optimistically, N is about 20 percent of L ; hence, if we feel that extraterrestrials can survive for about 250 million years (periods between mass extinctions), then N is equal to about 500 million communicating systems in our galaxy.
- However, the galaxy is large ($r = 50,000$ light-years and 6000 light-years thick). On average, there would be only one such system within $\left[\left(\left(3.14 \times (100,000/2) \times 2.0 \times 6000 \right) / 500,000,000 \right) \times (1/3.0) \right] / 2.0 = 23$ light-years of the Earth.
- This means that the odds of any intelligent civilization actually knowing that the Earth has intelligent life is possible because our broadcasts have traveled about 50 light-years into space, giving enough time for a response.
- Our galaxy is 1000 times larger than the distance our broadcasts have traveled. The problem is that the previous example was a very optimistic set of guesses.
- We know that $R^* = 6$ stars per year, and from the *Kepler* mission, we can now guess that $R^* \times f_s \times f_p \times n_e = 6 \times 0.1 \times \text{etaEarth}_{\text{Kepler}} = 6 \times 0.1 \times 0.3$. Therefore, $N = 0.18 f_l \times f_i \times f_c \times L$.
- Hence, for example, if $f_l = 0.5$ (life is robust), but intelligent life is rare, then $f_i = 0.1$ and $f_c = 0.3$ because it is common to broadcast something—but we really just don't know.

- In a more pessimistic case, $N = 0.18 \times 0.5 \times 0.1 \times 0.3 \times L = 0.0027L$. Therefore, pessimistically, N is about 0.3 percent of L ; hence, if we feel that extraterrestrials can survive for only about 30,000 years, then N is approximately equal to 80 communicating systems in our galaxy.
- However, the galaxy is large ($r = 50,000$ light-years and 6000 light-years thick). On average, there would be only one such system within $[((3.14 \times (100,000/2) \times 2.0 \times 6000)/80) \times (1/3.0)]/2.0 = 4000$ light-years of the Earth.
- This means that the odds of any intelligent civilization actually knowing that the Earth has intelligent life is impossible because our broadcasts have only traveled about 50 light-years into space.
- The terms f_i , f_c , and L are really where the Drake equation uncertainty is largest. One way to get a better handle on these terms is to look at the only data point we have: Earth.
- While it took just about 100 to 200 million years for life to start on Earth, it is sobering to note that intelligent life on Earth took another 3.5 to 3.7 billion years (about 30 times longer) to develop. Therefore, f_i is about 1, but f_c is likely much smaller.
- It is even more sobering to realize that our Sun is growing more dense and hotter in its core and, hence, is growing hotter and larger with time.
- In just about 600 to 1000 million years, the Earth will not be in the solar system's habitable zone. If we are still around, we can move on, but if intelligent life had required 4.7 billion years (just 20 percent longer), then the odds of intelligent life on the Earth would be zero.
- Of course, it might be that $N = 1$ and we are alone. Only with an active program that involves searching for extraterrestrial intelligence (SETI) can we start to discriminate between these

possibilities. Nature may have repeated itself over and over again; hence, we may not be so very special, so SETI is worth a try.

SETI

- In 1959, the prestigious journal *Nature* published a paper on radio SETI by Giuseppe Cocconi and Philip Morrison. The idea was to use the relatively new tools of radio astronomy to look for signals from extraterrestrial intelligence from space. Astronomer Frank Drake took up the challenge less than 1 year later.
- The goal of SETI is to use radio telescopes to listen to other stars and detect a signal of extraterrestrial origin. The problem concerns what bandwidth and frequency to look at, where to look, and when.
- The Allen Telescope Array (ATA) is the first large SETI telescope. It just started operations in 2007 and has just avoided closure by the support of the public, who will hopefully support it monetarily so that it can expand to 350 dishes in the future.
- It turns out that our star is quiet (dark) in the radio. In the microwave region of the spectrum, space is quite dark, and the Earth's sky is transparent and dark (no H₂O absorption). All of this leads to a range of 1 to 10 GHz as a top choice for SETI.
- For over 50 years, SETI has been looking around 1 to 10 GHz for a sign of a real extraterrestrial intelligence signal. There hasn't been any luck yet, but it is still early in the process.
- A real signal would drift in frequency slightly as the alien world changes velocity with respect to the telescope (unlike manmade signals from the Earth).
- Radio SETI was developed in the 1950s and 1960s, but now we use lasers to communicate. The issue is about contrast: Lasers cannot be brighter than aliens' host star (about 1026 watts). Hence, optical SETI only makes sense if the laser is aimed directly at Earth (only



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The Arecibo Observatory in Puerto Rico is famous for its 1000-foot telescope, which is involved in the search for extraterrestrial intelligence.

aliens within 50 light-years have any hope of knowing intelligent life on Earth).

- The problem is that you would need a laser more powerful than 10 gigawatts—even if very tightly beamed. Such tight beaming is beyond our technology with such high powers. There is too much laser power needed to overcome alien host starlight, which would still swamp the laser signal.
- Even aliens would be only able to produce such power in very short bursts at these levels, and they would only be able to target a limited number of systems. Hence, this type of communication is likely only from aliens that know we are here, which is inside of 25 light-years for optical SETI right now—of which the Drake equation shows there are likely none.
- However, if we could make a diffraction-limited beam in the optical on the receiving end and image the alien planet directly—away

from the glare of the alien star—then the laser only needs to be the same as an off-the-shelf kilowatt welding laser (about more than a million times less powerful).

- At these lower laser powers, aliens could target thousands of worlds, but how could they pick Earth? They could target every star that has a “living” planet—for example, one that has ozone in its reflected light spectrum. Even if there is no sign of intelligent life, a biosphere has been here broadcasting deep ozone for more than 2 billion years, so the entire galaxy now has evidence of Earth’s suitability for life.
- Advanced optical astronomy may be the key to SETI. Humans just need an adaptive optics (AO) system that works in the visible, and the Magellan AO project might be the solution. By using a high-resolution imager that has special adaptive optics technology, we can actually see the planet from which the laser could be sent from—separate from the star.

CETI

- In 1974, a message was beamed by Arecibo toward the globular star cluster M13 (25,000 light-years away). The message was binary and beamed a narrow bandwidth set of pulses up out of the scope. It has 1679 pixels, which is a product of only 2 primes: 73 rows and 23 columns.
- It is fairly unlikely that communication with extraterrestrial intelligence (CETI) would work; even human SETI researchers could not fully decode the message. It’s hard to avoid an anthropocentric trap: We think aliens will think like us because it’s all we know.
- SETI’s goal of listening seems like a much better idea than broadcasting—at least for us—the youngest civilizations in the galaxy. However, CETI could be dangerous. The natives rarely fare well from being colonized by an advanced race.

- Also, issues of who speaks for Earth, and what to say, have led to a moratorium on CETI. Of course, we are still beaming radio waves into space (but less now than in the 1980s), and our cities light up the night sky, so we are broadcasting—just not in a very focused way.

Suggested Reading

Davies, *The Eerie Silence*.

Impey, *The Living Cosmos*.

Questions to Consider

1. What is the most uncertain parameter in the Drake equation? Why?
2. Do you think that radio SETI can work? Why or why not?

The Fermi Paradox—Where Is Everyone?

Lecture 20

It is still too early in our quest for extraterrestrial intelligence to say for sure, but there doesn't seem to be any curious, very advanced civilizations nearby in our galaxy. Where is all of the evidence of these advanced civilizations that should be common throughout the galaxy? After all, there should be many (at least one) civilization that is much more advanced than us—perhaps one that is about 4 billion years older that has had plenty of time to completely colonize the whole galaxy. This lecture focuses on the Fermi paradox as it relates to SETI.

The Fermi Paradox

- There is a great deal of evidence that simple life should be common in our universe. At least on Earth, intelligent life arose within the habitability window of our Earth/Sun combination. About 5 percent of stars are single Sunlike stars, and of these, 3 to 30 percent will have habitable Earths.
- We know that only about 70 percent of those star systems are old enough today to have had evolution take place on them. We can even say that only just 0.1 percent of those remaining Earths do eventually go on to develop intelligent life.
- Then, the worst-case scenario is that the number of intelligent Earths over the 100 billion stars in the galaxy has been at least $\#C = 10^{11} \times 0.05 \times 0.03 \times 0.7 \times 0.001$, which means that approximately 100,000 past intelligent civilizations have arisen in the Milky Way.
- Is this too many past civilizations for the pessimistic case? The answer is not really. In fact, this is pretty pessimistic because if each of these lasts 30,000 years on average, then the Drake $N = 100,000 \times 30,000 / (\text{age of Milky Way})$. Hence, N equals approximately 0.3 communicating civilizations today—when we know that the real

answer is $N = 1$ as a minimum because of human beings—so we are not wildly overestimating $\#C$ based on previous results.

- If only 1 percent of intelligent civilizations do develop interstellar communication and/or probes, then that still leaves us with 1000 past civilizations that had advanced technology.
- In addition, there is good reason to believe that evolution combined with intelligence would push such civilizations to have cosmic wanderlust. After all, this wanderlust is hardwired into our DNA. Our past ancestors relied on this instinct to leave Africa in search of greener pastures.
- We have 1000 civilizations that have been spreading from star system to star system (by probes or other means). Some of them (about 50 percent) could be over a billion years old.
- The age estimate is simple. Because our galaxy has been element-rich enough for Earthlike planets for the last 10 billion years, some of these civilizations could be $10 - 4 = 6$ billion years old now, after the 4 needed for intelligent life to develop.
- Now we have about 500 individual billion-year-old civilizations. If they never develop any more sophisticated rockets than today's and, therefore, only travel at a leisurely 44 miles per second, then we can guess at the speed to cover the galaxy.
- Max Time = radius of galaxy/speed of probes = $50,000 \text{ light-years} \times (6 \times 10^{12} \text{ miles per light-year})/44 = 0.5 \times 10^{16} \text{ seconds} = 250 \text{ million years maximum to cover the galaxy.}$
- If we allow for slightly better rockets that can (over time) reach just speeds 100 times greater (just 2 percent the speed of light), then the time to explore the galaxy is approximately 2.5 million years.

- While 2.5 million years seems like a large number, it is not particularly a long time compared to the life of a billion-year-old civilization.
- In particular, one could imagine the use of von Neumann probes, which go from the home world directly to the next system and then replicate themselves there and set off to the next system. Certainly, one could imagine probes piggybacking on interstellar comets or free-floating planets and roaming the galaxy that way with little cost or materials needed from the home world.
- If we have about 500 of these civilizations that can each explore every system in the galaxy in about 2.5 million years, then every system should have been colonized or at least visited about 500 times in the past. That is the paradox. We have no evidence of such visits or communications.
- SETI doesn't pick up any such signal (even though the Earth has had strong biomarkers of life for over a billion years, so we would look interesting to an alien CETI program). There is no evidence of these past visits.

UFOs

- UFOs do exist in the sense that not everyone can make sense out of everything that they see in the sky. However, there are no examples of universally believed, high-quality observations of UFO phenomena.
- In fact, the general trend is that the more experienced the observer, the more sophisticated the equipment, the less likely there is a UFO sighting. Professional astronomers have well over 100 large telescopes operational every night and have never seen truly UFO-like behavior (either through the scope or outside of it).
- There are certainly rare phenomena that we do sometimes observe (such as electrical sprites), but to claim that because we do not understand the observed phenomena, it follows that the phenomena



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Unidentified flying objects (UFOs), or flying saucers, are spacecraft that are speculated to carry intelligent extraterrestrial life.

must be aliens in spaceships is an erroneous and invalid conclusion. UFOs are not a solution to the Fermi paradox, which was proposed by Enrico Fermi.

- It is often said that the reason all scientists don't believe in UFOs is because there is a massive conspiracy of all scientists, all military, and all governments to hold back this information from the general public. This is most definitely false.
- If an astronomer discovered a definitive extraterrestrial UFO, there would be a press release as soon as possible. While we might all want to believe, there is currently not much hard (high-quality) evidence to actually believe in.
- A big part of the problem with UFOs is that some rather misguided people keep making fake UFO videos and pictures. This just makes everything a mess and drives up UFO hysteria.

- For example, a few decades ago, hundreds of people in Belgium claimed to have seen triangular UFOs in the sky. They must be real if that many people saw them, right?

Is There a Solution to the Fermi Paradox?

- The paradox is that we can really make a strong case that if our ideas are valid about extraterrestrial intelligent life, then over the history of the Earth, the solar system has been visited many times (and the whole galaxy should have been explored). However, paradoxically, SETI has not detected anything, nor does any object in our solar system appear alien.
- There are many solutions to this apparent paradox—some with rather profound implications for intelligent life. Perhaps one of the more pessimistic solutions to the Fermi paradox is that intelligent life that has a strong wanderlust is also inherently hard on its own local environment (why else move on?). Hence, the very civilizations that would most likely spread through the galaxy would also burn up their local resources the fastest and possibly self-destruct in short order.
- There is some evidence that our own civilization is at a crossroads. Can we be good stewards of our resources and live long and prosper, or will we self-destruct in short order? No one knows for sure.
- If such civilizations self-destruct in less than the time required to send out a fleet of von Neumann probes, then all of those civilizations will have no galactic legacy.
- It is also worth considering that even our fastest probes required 2.5 million years to move around, so they must be small (to move so fast and last so long). Hence, it is possible that there are some signs of such visits in the asteroid or Kuiper belts, but we can't find them with today's technology because their footprint is too small.
- Perhaps part of the problem is that the current SETI searches are based on ridiculously anthropomorphic concepts of how an

advanced alien civilization 10,000 times older than our own would communicate or travel. We really have no idea.

- SETI is looking outdated even by Earth standards; high-powered radio is looking very 1960s compared to today's laser-based communications.
- The paradox is probably not quite as strong as it sounds. We still have a lot of searching to do before we can declare that there are no signs of visitation or communications.
- Of course, the solution to the Fermi paradox may be quite simple: It is not such a good idea to make yourself known to others for long-term survival in our galaxy. This sense of self-preservation is part of our past and may be common to many advanced civilizations.
- Perhaps the problem is that these intelligent civilizations exist (even right now nearby in our galaxy), but they are passive (perhaps even hiding any obvious signs of their civilization).
- This is certainly a depressing thought—for SETI fans—but based on how nervous we are about CETI, it seems a bit silly to think that no other space-exploring civilization would have similar concerns.
- An interesting question about the Fermi paradox is: How likely is it that there have been large empires in the galactic past and/or present? It is also interesting that 50 years of SETI has not seen any evidence of these civilizations, but there are many reasons why SETI has turned up nothing.
- Perhaps the best point is that we may not know what an ultra-advanced civilization looks like from afar. Such a civilization may very well not use radio, for example. It is certainly also true that maybe we have been visited in the distant past, but we can find no traces.

Suggested Reading

Davies, *The Eerie Silence*.

Impey, *The Living Cosmos*.

Webb, *If the Universe Is Teeming with Aliens ... Where Is Everybody?*

Questions to Consider

1. Do you think the Earth has been visited in the past, despite the lack of trace evidence?
2. Do you think the galaxy has been colonized in the past? Do you think there are undetected, intelligent galactic civilizations active in our galaxy right now?

Space Travel—A Reality Check

Lecture 21

While interplanetary travel is commonplace in science fiction, it is, in fact, nearly impossible to reach even the nearest star system in less than 900 years—even with future rockets. Either there will be a breakthrough in technology, or we will be stuck with very long journeys to the stars. These are real problems that cannot be wished away by writers of science fiction. In this lecture, you will learn how technically far humankind is from being able to travel between the stars in the future.

Interstellar Space Travel

- The ideal interstellar propulsion for an interstellar travel system would be one that could get you to other stars as quickly and comfortably as envisioned in science fiction. Before this can become a reality, scientific breakthroughs are needed, including the discovery of a means to exceed light speed, to propel a vehicle without propellant, and to power such devices.
- We need such major breakthroughs because space is really, really big. If the sun were the size of a typical, 1/2-inch-diameter marble, the distance from the Sun to the Earth, called an astronomical unit (AU) would be about 4 feet, the Earth would be barely thicker than a sheet of paper, and the orbit of the Moon would be about 1/4 inch in diameter. On this scale, the closest neighboring star is about 210 miles away—about the distance from New York to Boston.
- To help put this in perspective, consider that it takes light just over 8 minutes to cover that 4-ft AU. Light is the fastest thing that we know to exist. How long would it take to travel 210 miles if it takes over 8 minutes to travel just 4 feet? The answer is 4.2 years. Our nearest neighboring star, Proxima Centauri, is 4.2 light-years away.

- The problem is that we cannot travel anywhere near the speed of light. Light travels about 6 trillion miles in 1 year; for us, it would take much, much longer.
- At a more typical spacecraft speed, for example, the speed during the 3-day trip that it took the *Apollo* spacecraft to reach the Moon, a trip to the nearest star would still take over 900,000 years.
- Even if we consider the staggering speed of 37,000 miles per hour, which was the speed of the NASA *Voyager* spacecraft as it left our solar system years ago, the trip would still take 80,000 years.
- If we want to cruise to other stars within comfortable and fundable time spans, then we have to figure out a way to go faster than light.
- If we sent a canister about the size of a shuttle payload (or a school bus) past our nearest neighboring star and allowed it 900 years for it to make this journey, using chemical engines like those that are on a shuttle, there isn't enough mass in the universe to supply the rocket propellant that would be needed.
- The next possibility is nuclear rockets with a predicted performance that's 10 to 20 times better—but that's still not looking like a viable option. For a fission rocket, you would need a billion supertanker-sized propellant tanks to get you there, and even with fusion rockets, you would still need a thousand supertankers.



The *Apollo* spacecraft traveled to the Moon from the Earth in the 1960s and 1970s.

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- Even if we look at the best conceivable performance that we could engineer based on today's knowledge—for example, an ion engine or an antimatter rocket whose performance was 100 times better than the shuttle engines—we would need about 10 railway-tanker-sized propellant tanks.
- That doesn't include bringing along any propellant to let us stop when we get to the other star system, and it doesn't get us there quicker than 900 years. Once you take these considerations into account, then you're back at the incredible supertanker situation again—even for our best conceivable rockets.
- We'd really like to have a form of propulsion that doesn't need any propellant. This implies the need to find some way to modify gravitational or inertial forces or to find some means to push against the very structure of space-time.

Breakthroughs

- As technology evolves, a given device or method will reach a point at which it can no longer be improved. At this point, it has reached the limits of its underlying physical principles. To exceed this performance limit, a totally different device or method with different underlying physical principles is required—a breakthrough.
- Most spaceships that we have today, or envision in the near future, are designed around a basic principle of physics: For every action, there is an equal and opposite reaction. A jet plane, by forcing the hot gases of combustion out of the rear of its engines, moves the aircraft forward through the air. A rocket does the same thing, but because it carries both the fuel and the oxygen to burn it, in internal tanks, the rocket can operate in the vacuum of space.
- In a chemical rocket, the fuel provides both the power and the propellant. As the fuel burns and expands, it provides the power that then thrusts the waste products of the burning gases out the rear of the rocket.

- On the other hand, a solar sail uses the tiny pressure of light (from the Sun) to push it along. NASA's NanoSail-D demonstrated this technique, but it clearly is not going to get us to the stars quickly.
- The problem with the chemical rocket engines we use now is that they are relatively inefficient, and too much fuel is needed to take a ship great distances. New designs attempt to give spaceships greater range by increasing the power of the engine without increasing size or mass.
- One possible power source for future deep spaceships may be nuclear reactors. While nuclear fission reactors may produce potentially hazardous by-products that are environmental problems on Earth, they do produce a lot of power from a very small amount of fuel. The amount of uranium used up by a nuclear submarine traveling around the globe is about the size of a golf ball.
- A nuclear fission reactor on board a spaceship would produce lots of power, in the form of heat and electricity, but no propellant. In order to make the ship go forward, something must be expelled out the back. Propellant tanks filled with something inert like xenon would have to be carried on board.
- The electric power from the reactor could then be used to force charged particles (ions) of the propellant out the exhaust, which would move the ship forward.
- Such an ion thruster was successfully used on the NASA Deep Space 1 mission. Its ion drive allowed it to visit an asteroid and a comet around 2001.
- NASA has a future deep-space probe in planning that uses a fission reactor. It would leave our solar system and travel into space 1000 times more distant than the Earth is to the Sun—about 93,000,000,000 miles—to make astronomical observations.

- Even with a fission reactor, the amount of propellant needed to push a ship at high speed between the stars is still a problem. We can lessen the amount of propellant we need, though, by increasing the speed at which it is expelled while keeping the spaceship the same size. To increase the exhaust speed of the propellant requires more power. To increase the power, the nuclear fission reactor can be replaced with a nuclear fusion reactor.
- A fusion reactor can generate five times the energy from the same amount of fuel. The extra power can be used to expel the propellant faster, giving the ship more range or more speed. Unfortunately, we have yet to figure out how to make a fusion reaction work on Earth, except in the heart of an H-bomb explosion.
- Some fusion spaceship engine designs actually use many microexplosions to push the vessel forward. Tiny pellets of helium 3 would be detonated, each a miniature H-bomb, by powerful lasers 250 times per second. Using a design like this, a velocity of 12.2 percent of the speed of light might be obtained during an interstellar voyage.
- The ultimate power source for a spaceship is a matter-antimatter reaction. Often mentioned as the power source in the popular *Star Trek* television series and movies, it really exists. When matter and antimatter particles meet, their total mass is turned into energy. This means that a matter-antimatter engine would produce 200 times the power of a fusion engine for the same amount of fuel. The problem is that the resulting energy is extremely difficult to contain.

Traveling Faster Than Light

- Faster-than-light travel would simply be by far the best way to move around the cosmos. However, Einstein's special theory of relativity predicts that nothing can exceed the speed of light—but there is a loophole.
- Special relativity applies when space-time is flat. When space-time is curved, the theory applies only “locally”—that is, over regions of

space-time small enough to be considered flat. Consider the analogy of a plane that is tangent to a sphere. The flat geometry of the plane is a good approximation to the geometry of the sphere when the size of the plane is very small compared to the sphere's radius of curvature. Curved space-time has some loopholes.

- It is possible to travel much faster than the speed of light—if one can warp space-time to bring two different points together. In this case, travelers never go faster than the speed of light, but they find themselves in a faraway place by crossing over the warp. Hence, warp drives have become very popular in science fiction.
- Another way to travel faster than light is to pass through a wormhole. Current general relativity is pretty conservative about wormholes. The problem is that the very action of passing through one (in addition to killing you and your crew) causes the hole to collapse, trapping your remains in a black hole.

Credit: NASA/Glenn Research Center/Marc Millis.

Questions to Consider

1. How much fuel would be needed for a shuttle-like chemical rocket to reach the nearest star in 900 years?
2. Why do we think that with today's technology, it will be impossible to start traveling to the stars in our lifetimes?

Terraforming a Planet

Lecture 22

Asolution to the difficulties of interstellar travel is to transform Mars (or possibly Venus) into a more Earthlike planet. This process, called terraforming, is a long-term investment—like no other option we have considered. In this lecture, you will learn that while the best candidate for terraforming is Mars, our best short-term option is to take care of the Earth. If the reason we are trying to travel to the stars is to find an Earthlike planet, maybe it is simpler to just clean up our local neighborhood.

Terraforming Mars

- Terraforming is the process by which an uninhabitable environment is altered into an Earthlike environment that terrestrial plants and even humans could survive. Mars and Venus have both been considered as candidates for terraforming.
- The possibility of terraforming has become part of the common psyche. It has been used so frequently in science fiction plots that most of us know what it is—or at least think we do—and believe that it can be done. However, to actually take a planet and alter its natural environment to create a more terrestrial-friendly one is a complicated process, one that is not in our near future.
- To terraform a planet like Mars, the initial stages might take decades or centuries, and to transform the entire planet into an Earthlike habitat would take several millennia. Nevertheless, scientists have considered the possibilities.
- Mars seems to be the most likely candidate for terraforming because it is most Earthlike to begin with: The temperature range overlaps that of Earth, H₂O ice is present, and the length of the day is similar enough that organisms adapted to a 24-hour day/night cycle could adapt.

- We have already determined that liquid water needs to stay liquid on the surface of a planet for it to be habitable. Surface temperature needs to be greater than 0°C for at least part of the year for the kind of life we think of as typical to form and thrive.
- The temperature on Mars rises above 0°C at the equator, but the average temperature at the surface is -50°C to -60°C (-75°F), much below freezing. Even when the temperature on Mars does rise above freezing, the very thin (0.5 percent) atmosphere means that the water does not remain liquid, but quickly evaporates and refreezes.
- To terraform Mars would mean we would need to raise the daytime surface temperature to at or above freezing for at least part of the year on at least part of the planet. We also would need to give Mars a thicker atmosphere, both to give plants enough CO₂ to use and to give animals oxygen to breathe.

Raising the Temperature and Pressure on Mars

- To terraform Mars, we would need to increase the density of the Martian atmosphere way above its 0.5 percent of Earth's pressure. If Mars had more CO₂, then the atmosphere would warm up. At present, Mars does not contain enough atmospheric CO₂ to provide greenhouse warming.
- Raising the temperature of the polar caps would begin to sublimate the dry ice, which would raise the temperature further in a positive feedback loop. Increasing the temperature just south of the polar cap would be much easier than increasing the temperature of the entire planet.
- How would this initial temperature increase be accomplished? One suggestion has been to coat the polar caps with dark material (maybe by deliberately crashing small asteroids into Mars) so that they absorb more sunlight and sublimate. Another suggestion is that hardy, dark, cold-loving microbes could do the trick. Alternatively, orbital mirrors could be used to direct extra sunlight onto the polar caps.



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Through the process of terraformation, some scientists believe that it might be possible for life to survive and thrive on Mars.

- The temperature of the polar caps would only have to be raised by about 4°C (7°F) to initiate a feedback loop that would result in the solid CO_2 caps disappearing entirely. Whether there is truly enough stored CO_2 to create this loop is debatable. However, because CO_2 is already present on Mars in the polar caps, this method has distinct advantages—at least as an initial stage.
- For terrestrial plants to survive, sufficient amounts of CO_2 are critical. However, for humans, CO_2 levels cannot be too high. In the case of Mars, the amount of CO_2 needed to raise the temperature above freezing at the equator in summer (allowing a portion of the planet to support Earthlike life) would be deadly to humans.
- Earth does not have this problem because not as much CO_2 is needed to warm the planet to habitable temperatures because of Earth's proximity to the Sun.
- To terraform Mars so that both plants and humans can survive means we need to seek an alternative, or at least a supplement, to CO_2 to raise the surface temp.

- CFCs or PFCs have been suggested as a possible alternative, but they would need to be manufactured constantly, and the amounts needed to use these gases exclusively, without carbon dioxide or water as an additional greenhouse gas, would not be easy to achieve. Nevertheless, they would be possible, though expensive, with existing technology.
- One of the alternative gases to CO₂ to raise the atmospheric temperature is NH₃, or ammonia, which is a very efficient greenhouse gas. To obtain it we would need to convert nitrogen in the atmosphere, and we don't possess that technology yet. An alternative would be to deliberately crash ammonia-rich asteroids or comets into Mars.
- Another possible greenhouse gas is water vapor; it is actually responsible for the majority of the greenhouse effect on Earth. Like CO₂, water is present on Mars, though the exact amounts are unknown. Once again, melting the ice caps could release greenhouse gases into the atmosphere, or deliberately crashing comets into Mars could provide a supply of water. This can be done at least partly with materials already present on Mars and without creating an atmosphere hostile to human or other animal life.
- Another possible terraforming method is the use of large orbital mirrors. When placed a couple hundred thousand miles from Mars, the mirrors could theoretically reflect the Sun's radiation and heat up the Martian surface. However, these mirrors would need to be very large (with a total mirror diameter of about 60 miles—either one giant mirror or a number of small mirrors about 20 miles in diameter).
- Once the temperature of Mars is raised above the freezing point of water, the water deep under the Martian surface must be released from the rock it is stored in. Methods suggested are crashing asteroids into Mars or using a more narrowly focused mirror to melt the permafrost.

- Raising the temperature of Mars to above the freezing point of water, and giving it a thicker atmosphere, would only be the beginning of the terraforming process. Earth life would need to be introduced slowly, starting with bacteria or lichen tolerant of cold, dry conditions to convert some CO₂ into O₂ in the atmosphere, introducing more plants as conditions became warmer and wetter, and introducing animals once enough oxygen was present. Perhaps some creatures could be genetically engineered to be more tolerant of cold and dry conditions.
- No matter how much terraforming we do, we cannot change the fact that the gravity of Mars is only about 1/3 that of Earth. This means that the atmosphere will eventually escape unless it is replenished.
- If we wanted to terraform Mars and have the ecosystem survive for millions of years, rather than thousands, we would need to continue to introduce CO₂ and H₂O at a slow but constant rate to replace the gases that escape into space.
- While terraforming Mars is an exciting idea, the short-term feasibility is questionable. The amount of solid CO₂ in the polar caps will determine if it is at all possible in the long term, and the process would take thousands of years in even the best-case scenario.
- A final option is partial terraforming. Perhaps Valles Marineris could be covered over with some type of roof (for which the technology does not yet exist). The area within it is lower than the overall surface of Mars, giving it a higher atmospheric pressure, and because it is equatorial, it is relatively warm.
- It would be easier to raise the temperature and adjust the atmosphere within this greenhouse than it would be to do so for the entire planet, and it would still provide a large living area for humans.

Terraforming Venus

- The terraforming of Venus has also been considered (by Carl Sagan in 1961), though it would be even more difficult than terraforming

Mars. How could the temperature of Venus be brought down to a more clement level? One option involves moving asteroids into orbits so that they would collide with Venus. The impact would eject some atmosphere from the planet.

- However, there are not enough large asteroids in the solar system to do the job. In addition, this method would require the devastation of a large fraction of the Venus surface. Other options include using a sunshade to reduce the solar energy and adding dust to the upper atmosphere that would absorb or reflect sunlight before it reached the surface.
- Another option involves using microbes that could turn the excessive CO₂ into carbohydrates, which is an idea that is similar to what Carl Sagan suggested. Earth contains such bacteria, and possibly with some genetic engineering, they could complete this task on Venus. However, the carbohydrates created could react chemically with the oxygen that was produced and return CO₂ to the atmosphere. Unfortunately, none of these options are very likely to work.
- It is certainly much easier to try geoengineering on Earth than on Mars (with the slight downside that making a mess of things would be very bad for people on Earth). Currently, we are facing record-high levels of CO₂, a large part of which has been added this century by humanity. This is leading to greenhouse warming of the Earth. By the end of the century, we may have seriously altered our own climate through global warming. Of course, we could—and should—consider geoengineering approaches to alter this warming.

Suggested Reading

Jakosky, *The Search for Life on Other Planets*.

Questions to Consider

1. Could mankind ever take on a project like terraforming Mars, which would take thousands to millions of years to complete? Will such ultra-long-term projects ever be possible for such short-lived creatures like us?
2. Is terraforming one world into another even ethical? How do we know that there are no native organisms that we will drive to extinction?

The Future of Terrestrial Life

Lecture 23

In less than 1 billion years, humanity will have to leave the solar system to comfortably exist as we do now—on the surface of a habitable planet. The Earth will become hotter and less habitable in the short term due to the greenhouse effect and in the long term due to the Sun’s evolution. In this lecture, you will learn that we cannot be complacent about the long-term viability of the Earth. Eventually, mankind will have to move on to the stars or risk extinction.

The Warming of the Earth

- There is good evidence that the Earth is getting hotter. There are legitimate uncertainties in modeling such a big dataset as future Earth climate, but there is no doubt about the fact that there is more CO₂ than in thousands of years, and the Earth is starting to feel the warming from that extra greenhouse gas.
- The carbon cycle works on thousands-of-years timescales, so it will not help in the short term (in the next 100 years). This is especially true if the acidity of the oceans dramatically increases. Eventually, it is possible that a strong correction from the carbon cycle could occur, but only after thousands of years (at which time it could be too late).
- On average, the Earth is warming by about 1.5°F. Since 1960, the Arctic is now warmer by 4°C (7°F). The Earth is much warmer than it ever was in the last 1000 years, and there is good evidence that the temperature has suddenly started moving upward.
- Since the industrial revolution, we have been pumping quite a bit of CO₂ into the atmosphere. The natural sinks for CO₂ have not had a chance to scrub it out yet.



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If all of the existing glacier ice that exists on Earth melted, it would cause a world sea-level rise of approximately 300 feet.

- While it is clear that the Earth is warming up quickly and the CO₂ levels are at a record high, it is not clear how quickly the Earth will start warming up. The predictive part is tricky; it is a very complex system to simulate. We know it's going to get hotter, but by how much and how fast?
- The Intergovernmental Panel on Climate Change (IPCC), the leading international body for the assessment of climate change, has some educated guesses about global warming. The IPCC was established by the United Nations and World Meteorological Organization. Thousands of scientists at the organization work on each report that it publishes. The IPCC is policy neutral; there is no political mandate.
- The IPCC uses models to make predictions about global warming. In the best case, freezing emissions at levels from the year 2000, the global temperature would experience a 1°C increase. The most optimistic prediction from today's rate of pollution is that the global temperature would increase by 1.8°C (3.6°F). The most pessimistic prediction from today's rate of pollution is an increase of 4°C (7°F).

- Of course, even if the temperature rises about 2°C to 5°C (4°F to 9°F) and sea levels rise about 0.2 to 0.6 meters (0.7 to 2 feet), we are still living on a habitable planet in 2100. There will be widespread extinctions and a flooding of coastlines, but overall, most species would move, adapt, or die.
- In 2100, our Earth will likely be a hotter (wetter, cloudier, stormier?) place, but none of that changes the Earth from being firmly in the solar system's habitable zone. Therefore, either we cut today's CO_2 level by a factor of two by 2050 and limit the warming to 2°C (3.5°F) by 2100, or we don't, leading to a change of about 4°C (7°F).
- It turns out that it is so difficult to predict the next 100 years that there is little effort to make predictions about the next 10,000 years.
- There is the chance that the Earth's natural carbon cycle will start to scrub out the CO_2 naturally, but that will be hard if the oceans become too acidic (and kill the coral reefs) from the rapid warming. Therefore, it is very hard to say what will happen. It seems that we will need to do something to stop the Earth from getting too warm.

Geoengineering Approaches

- Given that the Earth's habitability is clearly finite, it is not crazy to think of the next step. First, we should cut down on pollutants—but that will only go so far. It is simply unlikely that we can check our dependence on fossil fuels. Then, we could consider geoengineering approaches.
- We only need to block 2 percent of the Sun's light to start cooling the Earth back down, so it seems possible. Volcanoes know how to block the Sun: By sending a thin layer of reflective particles high up into the Earth's atmosphere, they cool the Earth by increasing the reflectance of sunlight out of the atmosphere.
- We know that increasing our global high-altitude cloud cover by about 3 percent will cool off the planet. Therefore, a fleet of 1500 robot boats that spray salt water high up into the air could possibly

do it. The Magnus effect explains what happens when spinning cylinders hitting the wind make a driving force to push the boat. The cylinders also act as jets for the water droplets.

- Another approach, which we are already doing to some degree, is to fly airplanes and make extra clouds called contrails, which is short for “condensation trails.” If we could fly even higher and seed the stratosphere (like volcanoes do), then we could have even more cooling. The interesting point is that we certainly are cooling down the planet, by air pollution—even as we are heating it up. In fact, global dimming and global warming compete.
- Clouds dim the Sun’s heat or decrease global direct irradiance at the Earth’s surface (the solar constant). This was observed for several decades after the start of systematic measurements in the 1950s. The effect varies by location, but worldwide, it has been estimated to cause about a 4 percent reduction in heat over the 3 decades from 1960 to 1990. Planes have the same effect.

The Next Billion Years

- Assuming that we can stop from blowing ourselves up, completely ruining the Earth’s resources, or cooking it with a runaway greenhouse, then we could survive indefinitely on the Earth—or could we?
- What about asteroid impacts? Earth has not had a total extinction event impact for at least 3.9 billion years, so the greater than 300-kilometer objects are all now cleared out of Earth-crossing orbits. Objects like Vesta, one of the largest asteroids in our solar system, should never hit the Earth.
- However, there is something much more likely coming than an asteroid: In about 1 billion years, the Sun will be about 10 percent brighter—and then about 20 percent brighter in 2 billion years. This will be a really big deal.

- Between 1 and 2 billion years from now, the habitable zone of the Sun will have moved past Earth's 1-AU location. This might even occur sooner if the Earth's greenhouse gases keep increasing.
- The very worst scenarios of combining additional greenhouse gases and a warming Sun suggest that Earth's oceans could evaporate in about 0.1 to 1 billion years, leading to Venus-like conditions and a dead Earth (at least on the surface).
- The most obvious next step would be terraforming Mars. In 2 billion years, the Sun will be 20 percent more luminous and will have a maximum distance of about 1.54 AU, assuming a strong greenhouse on Mars. Therefore, it is possible that as the Earth gets too hot, we could planet hop to a somewhat warmer Mars.
- However, at best, Mars will never have more than 30 percent of the Earth's atmospheric pressure and 30 percent of its gravity. Moreover, this atmosphere will be constantly lost to space because there are no global protective magnetic fields on Mars. Furthermore, this CO₂ atmosphere will be in all likelihood poisonous to us.
- Maybe, though, the advanced human race could do a more advanced terraforming effort than we can imagine today, especially given that they would have millions of years to get it right. However, 5 billion years from now, the Sun is a red giant, is more than 200 percent brighter, and has a minimum distance of more than 2 AU, so Mars is also too hot for life. At that point, the solar system is dead for surface life.

Questions to Consider

1. How much hotter do you think where you live will be in 100 years?
2. Is global warming the largest near-term threat to humankind? Is it the largest long-term threat?

The Search for Another Earth

Lecture 24

Perhaps within about 100 million years (or sooner), the Earth will become too hot to be habitable on the surface. The oceans will have evaporated, and a runaway greenhouse will likely occur. Eventually, Earth will start to resemble the hellish surface of Venus. Hence, humanity will have to leave Earth or risk extinction, so we must start thinking of the next step. In this lecture, you will learn that we need to look to the stars and see if we can find a truly Earthlike living planet in our solar neighborhood.

Why Are Earths So Hard to Find?

- It is true that over 700 extrasolar planets have been detected, but mainly just by wobbles of the host star or slight dimming of the star as the planet passes in front of it. However, only a handful (such as Kepler-20e and Kepler-20f) are known to be Earth masses around a Sunlike star, but these are well inside 0.5 AU—way too hot for life and very far away.
- Kepler planets are typically over 1000 light-years away, which is impossibly far and faint for follow-up imaging work or as a destination for a future visit. However, we need to find similar-sized objects at 1 AU, and we also need to know if they are Earthlike: Do they have water oceans, oxygen atmospheres and ozone, or life? Kepler is not going to help here.
- It turns out that the techniques that we use to find nearby exoplanets all have limits for 1-Earth masses and 1-AU distances. Our main technique, the Doppler wobble, is insensitive to Earths. An Earth produces just about 10 centimeters per second of velocity—over 365 days—for the Doppler wobble, and we can at best measure about 100 centimeters per second today.
- The Kepler planets that are Earthlike are all too far away from the Sun to ever be of much interest in terms of travel. Only direct

imaging allows us to probe any discovered Earths for biomarkers, or signs of life.

- If direct imaging is the best way to detect the type of atmosphere a planet has, then why can't we do it? The main issue is that an Earthlike planet in the habitable zone will always be close to 10 billion times fainter than the host star. In addition, the separation of the star from the planet is only about 0.1 of an arc second (0.1 arc second is roughly the size of a dime 20 miles away) if the star is a close neighbor about 32 light-years away.
- In fact, until recently, the record detection of a faint object near a bright star was AB Dor C (at $0.15''$ 200 times fainter) with a Serial Digital Interface (SDI) camera used in Chile on the 8-m Very Large Telescope (VLT). The same team just detected HR 8799e at the 8.4-m Large Binocular Telescope (LBT), which is about 1000 times fainter at just $0.36''$ separations.
- The LBT adaptive optics (AO) system outperforms all other telescopes, but even with this super-powerful AO system, there is some "noise" in the images. This speckle noise looks a lot like the planets we are looking for, but astronomers have become very good at removing this noise to see fainter and fainter planets closer and closer in.
- It is pretty clear that the scattered light from the bright star swamps the light from the planet at the location of the planet. The HR 8799 planets are hot, massive Jupiters, which is why we can see them.
- What about faint Earths, which can only be seen in reflected light? Earths are



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A star cluster is held together by the mutual gravitation of the stars within it.

very faint and have very low mass compared to stars. An Earthlike planet will be about 109 to 110 times fainter than the star it orbits, so we have a big contrast problem. Even in our own solar system, it is hard to see the Earth without blocking the Sun.

- The Earth looks very faint at just 10 AU, so imagine how faint it is at 1,000,000 AU—which is a typical distance to the nearest star systems—making Earth 1000 billion times fainter and the contrast is still 10 billion.
- To image habitable Earths with terrestrial atmospheres will require highly specialized spacecraft that can suppress the starlight by 1 to 10 billion times at the location of the Earthlike planet (about 1 AU). Such optical devices, called coronagraphs, are already doing such suppression in labs around the world, proving that this type of light suppression is possible in principle.
- In 2009, there were a series of papers that showed that the High-Contrast Imaging Testbed (HCIT) did have the contrast needed to directly detect Earths. With raw contrasts of 109 to 110 after processing, these images showed that at a few tenths of an arc second, we could detect Earths directly. In particular, the work by Dr. Elizabeth Biller showed that a 2 percent spectrum could be obtained by such an instrument—if only we could get it into space.

Planet Finders

- While AO systems coupled with large telescopes can outperform Hubble Space Telescope (HST) in terms of contrast for exoplanet imaging, the ground-based system hit a contrast wall at 0.1" of 104 to 106 contrasts.
- To get to Earths (109 to 110), we clearly need to get smoother wave fronts so that the coronagraphs can work even better. The best way to accomplish this is in the vacuum of outer space.
- NASA envisioned a really impressive two-pronged approach to Terrestrial Planet Finders (TPFs). There would first be a

coronagraphic mission (TPF-C) followed by an interferometric mission (TPF-I).

- Unfortunately, due to technical challenges, cost overruns (like of most of NASA missions), and the current confusing funding environment at NASA, TPF-C and TPF-I seem to be indefinitely on hold. This is despite the top ranking that looking for biomarkers on habitable planets received from the 2010 decadal review of astronomy.
- Currently, funding is very tight at NASA, and ESA has put its planet image on hold as well. The massive cost overrun of the James Webb Space Telescope (JWST) has hurt many other new missions. The Space Interferometry Mission (SIM) was, for example, even mainly built but never finished.
- However, smaller missions are being planned. One such example is a 0.7-m Explorer-class (\$200 million) mission for imaging disks around nearby stars—the Exoplanetary Circumstellar Environments and Disk Explorer (EXCEDE).
- EXCEDE (with principal investigator Glenn Schneider at the University of Arizona) was selected in the last 2011 Explorer round for further development of technology to enable direct high-contrast imaging from space.
- The key to all of this effort is to directly image exo-Earths and to actually take a reflection spectra of the atmosphere of the planet. Certainly, one could use a TPF-C to take low-resolution spectra of exo-Earths.
- However, what are we looking for in this spectra to tell us if the planet is really Earthlike? Obviously, it should be in the habitable zone. Then, it can have an atmosphere with H₂O, O₂, and O₃. In particular, ozone (O₃) is a good indicator of life on another planet.

- The Earth has a pretty rich mid-infrared spectrum so that even at low-spectral resolutions (as we would have from a faint exo-Earth), we could learn a lot. The TPF-I mission in particular would be good at these wavelengths.
- It is even possible that looking at the spectrum of the star before and after a transit making a transmission spectrum, we might learn about a few bright nearby transiting super-Earths with the future 2018 JWST mission.

Leaving the Solar System

- Assuming that we do find a great planet that is truly Earthlike, then it might be a good idea to go there—before it gets too hot here. There are about 24 Earthlike planets within 32 light-years waiting to be discovered.
- TPF will tell us which of these have biomarkers and are truly Earthlike— H_2O and O_2 with O_3 and life—so if we are lucky, within 32 light-years, one of the 24 planets is truly a living, habitable Earth for us.
- A 20-light-year trip is about 5 times larger than the 4.2-light-year trip from Lecture 21. However, with long-term planning and sustained effort, there is no physical reason that ships could not travel to new worlds 20 light-years away—as long as they could travel for about a thousand years.
- That thousand-year journey in space might result in some evolutionary changes that would make us somewhat different. Imagine 40 generations that have never been on solid ground. Defense Advanced Research Projects Agency (DARPA) has just starting a long-range planning institute, 100 Year Starship, for this goal.
- We now know that rocky Earthlike planets exist, and we know that a spectrum is needed to tell if a planet has biomarkers of life.

However, today's telescopes are not capable of the very tricky process of detecting such faint Earthlike planets in reflected light.

- Highly specialized optical systems will be needed to tease out light from the planet 10 billion times fainter than the star just $0.1''$ of an arc second away. Fortunately, it has been proven that this level of light control is possible. In fact, in several labs, combining deformable mirrors (DMs) and coronagraphs has shown that these contrasts can be reached.
- Hopefully in the near future, a pathfinder for these systems (like the NASA EXCEDE mission) will be launched. Then, we should have true spectra from TPF-C and TPF-I of the nearby habitable Earths. Then, maybe we'll know if we are alone or not for the first time—and where to go in the far future because humankind cannot live on Earth indefinitely.
- After all, wandering to a new place to explore new worlds and exploit new resources is hardwired into our DNA. We are wanderers and explorers by nature, and we are just starting to set our sights on the stars—setting the stage for humankind's biggest adventure yet.

Suggested Reading

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Questions to Consider

1. What new technology enables astronomers to build coronagraphs that can suppress starlight enough to image Earthlike planets around bright stars (at least in lab simulations)?
2. Do you think that NASA, or ESA, has the vision (and willpower) to capitalize on this new technology to actually build a dedicated spacecraft to discover nearby Earthlike planets and detect life on them?

Astrobiological Timeline

13.8 billion years ago: The big bang—our universe forms as a super dense, super hot accelerating ball of plasma.

3 minutes after the big bang: The universe cools and consists of hydrogen (75 percent) and helium (about 25 percent) nuclei.

500 million years after the big bang: Our galaxy (the Milky Way) forms; stars are starting to enrich the galaxy with heavier elements needed for life.

4.55 billion years ago: The Sun starts forming.

4.54 billion years ago: Earth and the solar system's planets form.

4.5 billion years ago: The so-called big splat creates our Moon.

4.1–3.85 billion years ago: The late heavy bombardment rains down massive impacts onto the young Earth, making surface life impossible.

3.8 billion years ago: The earliest hints of life on Earth.

3.45 billion years ago: Colonies of single-celled, prokaryotic, photosynthesis-based bacteria like stromatolites become common.

~2.5 billion years ago: Earth starts to have significant oxygen in its atmosphere.

~1.8 billion years ago: Larger eukaryotic cells appear.

~1 billion years ago: Rise of multicellular life.

600 million years ago: Rise of simple animals.

580–500 million years ago: Rise of complex animals.

250 million years ago: P-T extinction event—90–95 percent of all marine animals go extinct.

65 million years ago: K-T impact event and extinction of the dinosaurs.

2.5 million years ago: Rise of genus *Homo*.

200,000 years ago: Appearance of modern humans.

150 years ago to present: Manmade pollution increases atmospheric CO₂.

100 years into future: Planet warms by about 3–5°C (about 5–9°F).

2 billion years into future: The Sun is 20 percent hotter; Earth's surface likely becomes uninhabitable.

5 billion years into future: The Sun becomes a red giant; the solar system becomes uninhabitable.

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Internet Resources

<http://astrobiology.nasa.gov>. This is the main NASA astrobiology site—probably the best, and biggest, website on the Internet.

<http://mars.jpl.nasa.gov/msl>. This is the site of NASA's Mars Science Laboratory. The latest results of the Curiosity rover's adventures on Mars can be found on this site.

http://www.nasa.gov/mission_pages/cassini/main/index.html. This is the site with the latest findings from the *Cassini* mission to Saturn, its rings, and moons (such as Titan and Enceladus).

<http://solarsystem.nasa.gov/galileo/index.cfm>. This is NASA's *Galileo* site, where you can still find some of the best information on Jupiter and its moons (such as Europa and Ganymede).

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<http://exoplanet.eu>. The best up-to-date website with detailed information on all known extrasolar planets and their parent stars.

<http://www.nasa.gov/kepler>. This is the NASA *Kepler* mission home page, where you can research the latest extrasolar planets found by *Kepler*.

<http://www.space.com>. A general site for the space sciences with up-to-date news on the big stories from NASA, ESA, and the astronomy community.

<http://100yearstarshipstudy.com>. A good site to see a real effort at starting the process of traveling to the stars.

<http://www.nasa.gov/centers/glenn/technology/index.html>. A site that displays the latest research on spaceship propulsion from NASA.

<http://www.ipcc.ch>. A handy site for climate change predictions.